NAS8-36289

# THERMAL CONTROL SURFACES EXPERIMENT
# INITIAL FLIGHT DATA ANALYSIS

## *FINAL REPORT*

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*June 1991*

# THERMAL CONTROL SURFACES EXPERIMENT

# INITIAL FLIGHT DATA ANALYSIS

# FINAL REPORT

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THERMAL CONTROL SURFACES EXPERIMENT

LIST OF ACRONYMS

| | |
|---|---|
| A-D | - Analog to Digital |
| AO | - Atomic Oxygen |
| CCD | - Charge Coupled Device |
| CPU | - Central Processor Unit |
| CRT | - Cathode Ray Tube |
| DACS | - Data Acquisition and Control System |
| DC | - Direct Current |
| DOD | - Department of Defense |
| EMI | - Electromagnetic Interference |
| GRU | - Ground Reproduce Unit |
| GSE | - Ground Support Equipment |
| GSFC | - Goddard Space Flight Center |
| HST | - Hubble Space Telescope |
| IITRI | - Illinois Institute of Technology Research Institute |
| IR | - Infrared |
| IRS | - Internal Reflection Spectroscopy |
| JSC | - Johnson Space Center |
| KSC | - Kennedy Space Center |
| LaRC | - Langley Research Center |
| LDEF | - Long Duration Exposure Facility |
| LEC | - Lockheed Electronics Company |
| M&D | - Micrometeoroid and Debris |
| M&P | - Materials and Processes |
| MSFC | - Marshall Space Flight Center |

| | | |
|---|---|---|
| MTA | - | Multiple Time Averaging |
| NASA | - | National Aeronautics and Space Administration |
| PI | - | Principal Investigator |
| PRT | - | Platinum Resistance Thermometer |
| PSD | - | Phase Sensitive Detector |
| SIG | - | Special Investigative Group |
| SRB | - | Solid Rocket Booster |
| TCSE | - | Thermal Control Surfaces Experiment |
| THERM | - | Thermal Measurement System |
| UAH | - | University of Alabama - Huntsville |
| UV | - | Ultraviolet |
| VCM | - | Vacuum Condensable Material |

## 1.0 INTRODUCTION

The natural and induced long term effects of the space environment on spacecraft surfaces are critically important to many of NASA's future spacecraft--including the Space Station. The damaging constituents of this environment, as illustrated in Figure 1, include thermal vacuum, solar ultraviolet radiation, atomic oxygen, particulate radiation, and the spacecraft induced environment. The inability to exactly simulate this complex combination of constituents results in a major difference in the stability of materials between laboratory testing and flight testing. To study these environmental effects on surfaces--particularly on thermal control surfaces--the Thermal Control Surfaces Experiment (TCSE) was proposed for the National Aeronautics and Space Administration (NASA) Long Duration Exposure Facility (LDEF) mission. The TCSE was selected as one of the first six experiments for the LDEF.

On April 7, 1984, the LDEF--with the TCSE as one of its complement of 57 experiments--was deployed in low-earth orbit by the Space Shuttle. The LDEF was to have been retrieved after 9 to 12 months in orbit. However, due to the Shuttle redesign effort and launch schedule priorities, the LDEF retrieval was delayed approximately 60 months--until January 12, 1990. After retrieval by the Shuttle, the TCSE was deintegrated from the LDEF at the Kennedy Space Center (KSC) and returned to the Marshall Space Flight Center (MSFC) for analysis on March 7, 1990.

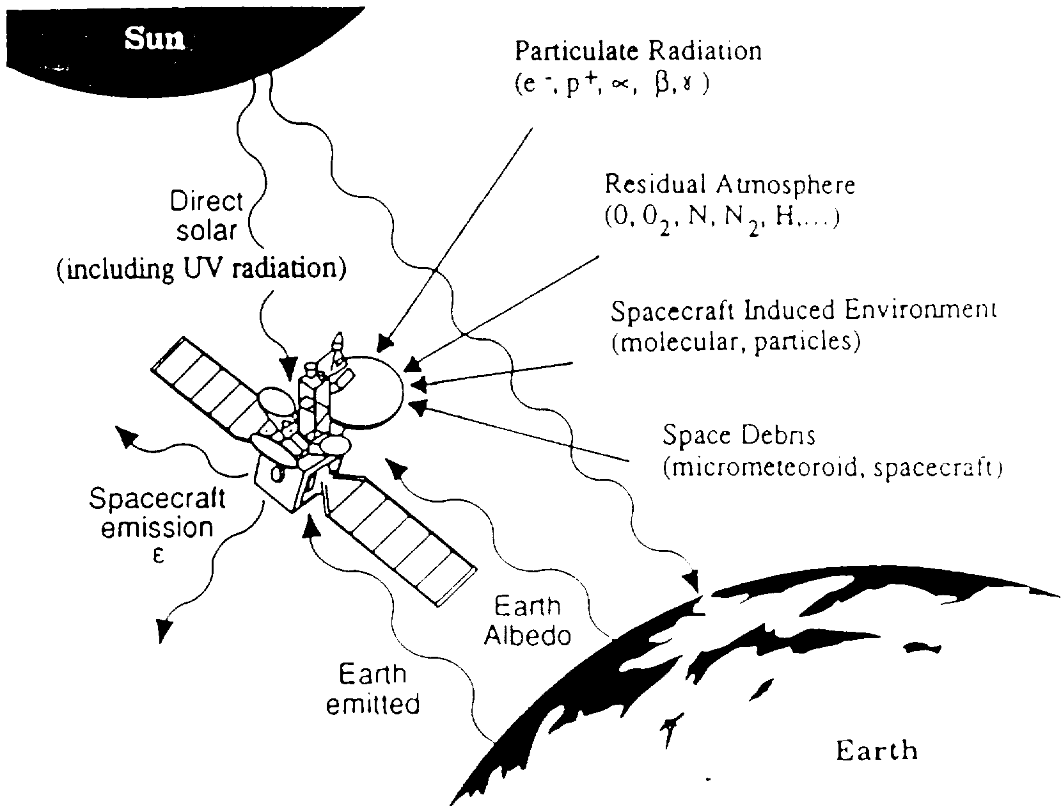



Figure 1 - The Spacecraft Environment

The TCSE was a comprehensive experiment that combined in-space measurements with extensive post-flight analyses of thermal control surfaces to determine the effects of exposure to the low earth orbit space environment. The TCSE is the first space experiment to measure the optical properties of thermal control surfaces the way they are routinely measured in the laboratory. While the TCSE marks a milestone in understanding the performance of materials in space, other experiments similar to the TCSE will

be required to fully understand the diverse effects of the space environment. These experiments will provide additional optical and environmental monitoring.

This initial analysis effort is but the first of a series required to derive the greatest benefit from the TCSE for future space missions. This effort concentrated mainly on the flight material samples and only considered the TCSE flight system performance to the extent required to analyze the flight data and samples. Detailed materials analyses of the TCSE components and enclosure also remain to be performed. Additionally, a more comprehensive analysis of the flight materials is required.

The TCSE flight system is the most complex mechanism (other than the LDEF) ever retrieved from space after nearly six years of exposure. It represents a microcosm of the large electro-optical payloads in development by NASA, Department of Defense (DoD), and industry. A future detailed systems analysis of the TCSE will provide a better understanding of the performance of complex systems, subsystems, and components in the space environment.

This initial analysis of the TCSE was performed under contract NAS8-36289 for NASA/MSFC. This is the final report for this effort and describes the TCSE objectives, flight hardware, and initial results of the TCSE mission. Results from other related LDEF and TCSE analyses are included in this report, where appropriate, to provide a better understanding of the results of this effort. Section 2 describes the TCSE objectives, experimental method, and the flight hardware. Section 3 summarizes the

LDEF and TCSE mission. Section 4 presents the performance and anomalies of the TCSE hardware system. Section 5 discusses the initial results of the materials experiment. Section 6 is a summary of this effort.

## 1.1 TCSE Program Participants

The success of the TCSE is due to the work of many NASA and contractor personnel. The TCSE was originally proposed in 1975 by the Principal Investigator (PI) Mr. Donald R. Wilkes and Co-Investigator Mr. Harry M. King. At that time, both investigators were with the National Aeronautics and Space Administration's Marshall Space Flight Center (NASA/MSFC). In 1977 , a competitive procurement was issued for the development of the TCSE flight hardware. Aerojet ElectroSystems of Azusa, California was selected as the prime contractor. They designed, fabricated, and assembled the TCSE protoflight unit and performed the initial functional testing. Due to a two year delay in the LDEF program and associated funding problems, the TCSE development contract with Aerojet was terminated and the partially operating TCSE instrument delivered to MSFC. The TCSE protoflight unit was then completed and tested in-house at MSFC with the assistance of Radiometrics, Inc. in Huntsville, Alabama.

The TCSE initial post-flight analysis was performed as a joint effort by the MSFC Materials and Processes (M&P) Laboratory and the PI and his staff at AZ Technology.

There are far too many participants in the TCSE program to list in this publication. Figure 2 is a list of the participants

who had formal responsibility for the success of the TCSE. Significant credit for the TCSE success should also go to the LDEF Chief Scientist, Dr. William Kinard, and the entire LDEF staff along with the Shuttle astronauts who deployed and retrieved the LDEF.

PRE-FLIGHT

NASA/MSFC

| | |
|---|---|
| Principal Investigator - | D. R. Wilkes, Space Sciences Laboratory |
| Co-Investigator - | H. M. King, M&P Laboratory |
| Chief Engineer - | L. W. Russell, Space Sciences Laboratory |
| | G. M. Arnett, Science & Engineering |
| Program Manager - | B. J. Schrick, Special Projects Office |

NASA/LaRC

| | |
|---|---|
| Guest Investigator - | W. Slemp |

Aerojet ElectroSystems

| | |
|---|---|
| Project Manager - | M. J. Brown |
| Chief Engineer - | R. Emerling |

Radiometrics

| | |
|---|---|
| Lead Engineer - | R. Schansman |

POST-FLIGHT

NASA/MSFC

| | |
|---|---|
| Co-Investigator - | J. M. Zwiener, M&P Laboratory |

AZ Technology

| | |
|---|---|
| Principal Investigator - | D. R. Wilkes |
| Lead Engineer - | L. L. Hummer |
| | M. J. Brown |

## 2.0 EXPERIMENT DESCRIPTION

The Thermal Control Surfaces Experiment was designed to be a comprehensive experiment to study the effects of the space environment on thermal control surfaces. This section describes the basic objectives of the TCSE and the experimental method, the materials tested, and the TCSE flight hardware.

### 2.1 TCSE Objectives and Experimental Method

The basic objective of the TCSE on the LDEF was to determine the effects of the near-Earth orbital environment and the LDEF induced environment on spacecraft thermal control surfaces. In summary, the specific mission objectives of TCSE were to:

- o Determine the effects of the natural and induced space environment on thermal control surfaces
- o Provide in-space performance data on thermal control surfaces
- o Provide in-space comparison to ground-based environmental testing of materials
- o Develop and prove instrumentation to perform in-space optical testing of materials.

To accomplish these objectives, the TCSE exposed selected material samples to the space environment and used in-flight and post-flight measurements of their thermo-optical properties to determine the effects of this exposure.

The TCSE hardware was designed to expose 25 "active" and 24 "passive" test samples to the LDEF orbital environment. The active and passive test samples differed in that the space effects on the passive test samples were determined only by pre- and post-flight evaluation. The optical properties of the 25

"active" samples were measured in-space as well as in pre- and post-flight analysis.

The "passive" samples were duplicates of critical "active" samples as well as specially prepared samples for surface analysis techniques, such as Internal Reflection Spectroscopy (IRS). The post-flight analysis of these passive samples, as well as the active samples, is used to determine the effects of the LDEF mission in more detail than is feasible with "in-situ" measurements. Of special importance are the detailed surface effects of the Atomic Oxygen (AO) fluence and the identification of any molecular contaminant film on the sample surfaces.

## 2.2 <u>In-Space Measurements</u>

The primary TCSE in-space measurement was hemispherical reflectance as a function of wavelength (100 wavelength steps from 250 to 2500 nm) using a scanning integrating sphere reflectometer. The measurements were repeated at preprogrammed intervals over the mission duration.

The secondary measurement used calorimetric methods to calculate solar absorptance and thermal emittance from temperature-versus-time measurements. The "active" sample surfaces were applied to thermally isolated (calorimeter) sample holders. To aid in the calorimetric calculations, three radiometers were used to measure the radiant energy (solar and Earth albedo, Earth albedo, and Earth infrared (IR) emitted) incident upon the samples. The radiometers also determined the total exposure of the samples to direct solar irradiance. The TCSE measurements are

more fully described in section 2.4.

## 2.3 Flight Samples

The materials chosen for the TCSE mission comprised the thermal control surfaces of the greatest current interest (in 1983) to NASA, MSFC and the thermo-physical community. The samples flown on the TCSE mission were:

- A276 White Paint
- A276/OI650 Clear Overcoat
- A276/RTV670 Clear Overcoat
- S13G/LO White Paint
- Z93 White Paint
- YB71 White Paint
- YB71 over Z93
- Chromic Acid Anodize
- Silver/FEP Teflon (2 mil)
- Silver/FEP Teflon (5 mil)
- Silver/FEP Teflon (5 mil Diffuse)
- White Tedlar
- D111 Black Paint
- Z302 Black Paint
- Z302/OI650 Clear Overcoat
- Z302/RTV670 Clear Overcoat
- KRS-5 IR Crystal
- Silver

Many of these materials were selected because they are good reflectors of solar energy while also being good emitters of thermal energy to the cold sink of space, i.e. they have a low solar absorptance ( $\alpha_S$ ) and a high room temperature emittance ( $\varepsilon_T$ ). The range of low $\alpha_S / \varepsilon_T$ thermal control surfaces include materials that were expected to be very stable for the planned 9-12 month LDEF mission while others chosen because they were expected to degrade significantly.

A second class of materials flown on the TCSE was black paints. These are important as solar energy absorbers and light

absorbers for science instruments.

Some of the materials were expected to react with the residual atomic oxygen at the LDEF orbital altitude. Transparent coatings were applied over a few of these samples to protect the sample from AO.

The remainder of this section discusses each of the materials flown on the TCSE.

### 2.3.1 A276 White Paint

Chemglaze A276 white paint is a Titanium Dioxide ($TiO_2$) pigment in a polyurethane binder. It has been used on many space vehicles including Spacelab.

In early Shuttle experiments[1] and ground testing, A276 had been shown to be susceptible to erosion by atomic oxygen. It had been suggested that clear overcoatings would protect AO susceptible coatings. The effectiveness of two protective coatings over the A276 were evaluated on the TCSE. These overcoatings were Owens Illinois OI650 glass resin and RTV670.

A276 is manufactured by the Lord Corporation Chemical Division. The samples for the TCSE were prepared by personnel in the Materials and Processes Laboratory, NASA/MSFC.

### 2.3.2 S13G/LO White Paint

S13G/LO white paint has been the most widely used white thermal control coating for space vehicle thermal control. S13G/LO consists of zinc oxide (ZnO) pigment in a General Electric RTV602 methyl silicone binder. The pigment particles were

treated with potassium silicate before processing into paint to inhibit the photodesorption of oxygen from the ZnO pigment when subjected to solar UV exposure.[2]

The S13G/LO formulation used for the TCSE samples is no longer available because the RTV602 binder is not currently manufactured. A new methyl silicone binder is used in S13G/LO-1 white paint which is a replacement for S13G/LO. S13G/LO and S13G/LO-1 are manufactured by the Illinois Institute of Technology Research Institute (IITRI). IITRI prepared the S13G/LO samples for the TCSE. Figure 3 summarizes the TCSE samples prepared by IITRI.

| Coating Material | Sample Number | Coating Thickness (mils) | Batch Number |
|---|---|---|---|
| S13G/LO | C92 | 12.0 | I-097 |
| | P7 | 9.5 | I-097 |
| Z93 | C95 | 4.5 | I-100 |
| | P5 | 5.0 | I-100 |
| | P6 | 6.5 | I-100 |
| YB71 | C96 | 6.5 | I-061 |
| | C97 | 9.5-10.5 | I-061 |
| | P1 | 9.5 | I-099 |
| | P2 | 9.0 | I-099 |
| YB71 over Z93 | C93 | 9.0-9.5 | I-061 (YB71) |
| | C94 | 8.5-9.5 | I-100 (Z93) |
| | P3 | 11 - 12 | |
| | P4 | 10.0 | |
| D111 | C99 | 2.5 | I-101 |
| | P10 | 4.0 | I-101 |

Figure 3 - IITRI Prepared TCSE Flight Samples

### 2.3.3 Z93 White Paint

Z93 is another widely used white thermal control coating that is manufactured by IITRI. Z93 is the same zinc oxide pigment as S13G/LO but in a potassium silicate binder. IITRI also prepared the Z93 samples for the TCSE.

### 2.3.4 YB71 White Paint

YB71 white paint is a zinc orthotitanate ($Zn_2TiO_4$) pigment in a potassium silicate binder. When the TCSE samples were prepared, YB71 was just completing development. YB71 offered the potential for solar absorptance values less than 0.10 while maintaining an emittance of 0.90. This coating also offered improved stability in the space environment, especially for particulate radiation exposure.

Because the manufacturing and application process was not finalized when the TCSE samples were prepared, the $\alpha_S$ values for the YB71 were somewhat higher than desired ( $\alpha_S$ = 0.11 to .15). Somewhat lower $\alpha_S$ values for the TCSE samples were achieved by applying a primer coat of Z93 white paint before the YB71 was applied. Current versions of the YB71 have resolved this problem and $\alpha_S$ values around 0.08 are being achieved.

YB71 is manufactured by IITRI, who also prepared the TCSE samples.

### 2.3.5 Chromic Acid Anodize

Two chromic acid anodized aluminum samples were tested on the TCSE. These samples were provided by Mr. Wayne Slemp of Langley Research Center (LaRC) who is a TCSE guest investigator.

Anodized coatings have long offered the potential for stable coatings for large surfaces and are being considered for use on Space Station Freedom.

### 2.3.6 Silver Teflon Surfaces

Silverized FEP Teflon is another widely used thermal control surface. Two different thicknesses of silver Teflon were flown on the TCSE -- 2 mil and 5 mil. The 2 mil material was used on the TCSE front cover as part of the passive thermal control system. A sample of the 2 mil silver Teflon was also flown on the active sample array. The 2 mil material was attached to the substrate with 3M Y-966 acrylic pressure sensitive adhesive tape. A Teflon squeegee was used to remove air bubbles followed by a wipedown with isopropyl alcohol.

Two configurations of the 5 mil silver Teflon material were flown on the TCSE sample array -- the normal specular type and an embossed or diffuse type. The normal silver Teflon material has a mirror like finish which is undesirable for some applications. The diffuse material has a dimpled pattern embossed into its surface to minimize specular surface reflections. The 5 mil material was attached to the sample substrates with P223 adhesive.

The silver Teflon used on the TCSE was manufactured by Sheldahl. The 2 mil calorimeter sample was prepared by Aerojet ElectroSystems. The TCSE cover material was applied by personnel in the Materials and Processes Laboratory, MSFC. The 5 mil samples were provided by Wayne Slemp of LaRC. Teflon is a

trademark of Dupont.

### 2.3.7 White Tedlar Film

White Tedlar is a pigmented delrin plastic film manufactured by Dupont. White Tedlar was a candidate for the external covering of insulating blankets used on spacecraft. This material was flown on the TCSE because its solar absorptance was expected to degrade a measurable amount in the planned 9-12 month LDEF mission. The TCSE Tedlar samples were prepared by the Materials and Processes Laboratory at MSFC.

### 2.3.8 D111 Black Paint

The performance of many spacecraft and instruments depends on light absorbing coatings. D111 black paint was developed by IITRI as a stable diffuse coating for this application. The D111 formulation is a bone black carbonaceous pigment in an inorganic potassium silicate binder. D111 coatings provide high absorptance over the solar region (250 - 2500 nm) with a near zero Vacuum Condensable Material (VCM). The TCSE D111 samples were prepared by IITRI.

### 2.3.9 Z302 Black Paint

Chemglaze Z302 is a gloss black paint from Lord Chemical. Z302 is an aromatic polyurethane coating with a carbon black pigment. It was used on the aperture door of the Hubble Space Telescope as a light absorber coating. The specularity of Z302 was required to reflect any light, not absorbed, away from the telescope aperture and prevent scattering into the field-of-view.

Laboratory and flight testing of Z302 determined that this material was very susceptible to AO erosion.[1] Clear overcoatings might be used to protect the Z302 from AO. The effectiveness of two transparent protective coatings were evaluated on the TCSE -- Owens Illinois OI650 glass resin and RTV670. The Z302 samples for the TCSE were prepared by the M&P Laboratory, MSFC.

2.3.10 Other Samples

Two other types of samples were flown on the TCSE passive sample array -- two KRS-5 crystals and three silver samples. The KRS-5 crystals were flown to evaluate any molecular contamination deposited on the TCSE sample surfaces. KRS-5 crystals are typically measured in an internal reflection infrared spectrometer. This measurement can provide infrared absorption spectra from very small amounts of material deposited on the surface of the crystal. This spectra can aid in determining the species of any deposited contaminant.

The silver samples were flown on the TCSE to evaluate the fluence and behavior of AO. These samples consisted of three stacked silver coated disks. The top two disks had a pinhole in the center of each disk to act as a pinhole camera and evaluate the directionality and accommodation of the incident AO molecular beam. The silver samples were designed and built by Dr. Palmer Peters of the MSFC Space Science Laboratory and Dr. John Gregory of the University of Alabama - Huntsville (UAH).

The post-flight analyses of these special samples have not been completed and will be presented in a later report.

### 2.4 TCSE Flight Hardware

The TCSE is a completely self-contained experiment package; providing its own power, data system, and pre-programmed controller for automatically exposing, monitoring, and measuring the sample materials. The TCSE was developed as a protoflight instrument where one instrument was built, made to work within required specifications, tested, and flown. Environmental qualification testing was performed at MSFC that included vibration, thermal vacuum, and electromagnetic interference (EMI) tests.

The TCSE was built in a 305 mm (12 in.) deep LDEF tray (see Figure 4). The active and passive samples were mounted in a semicircular pattern on a circular carousel with three radiometers. The carousel is tilted at 11 degrees from the outer tray surface to allow a 115 mm (4.5 inch) diameter integrating sphere to fit between the deep end of the carousel and the outer shroud. This design satisfied the LDEF requirements to remain within the outer edges of the tray and also provided a field of view of space greater than 150 degrees for the samples. This design maintained mechanical simplicity and inherent reliability.

Figure 5 shows the basic specifications for the TCSE flight hardware.

#### 2.4.1 Sample Carousel

The TCSE sample carousel design enabled the test samples to be either protected from or exposed to the space environment as well as to be positioned for optical measurement. Figure 6 illustrates the sample positions on the carousel during various

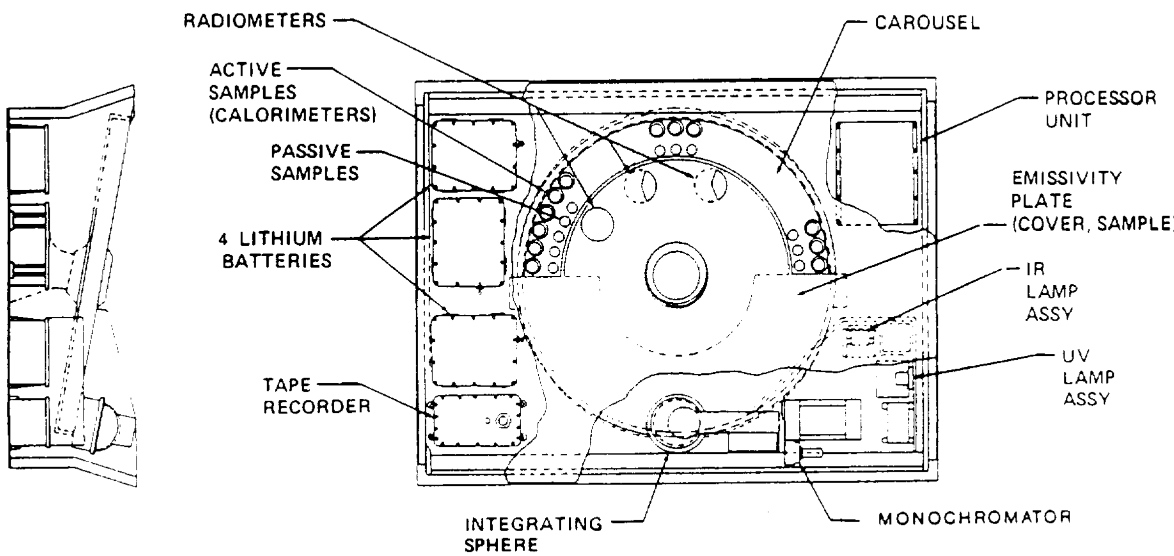



Figure 4 - TCSE Assembly

| | |
|---|---|
| Size | 1.24m x .84m x .30m<br>(48.75 x 33 x 12 in.) |
| Weight | 80.5kg (177 Pounds) |
| System Controller | 1802 MicroProcessor |
| Battery Capacity | 72 Amp Hours<br>at 28 VDC |
| Data Recorder<br>-Capacity | Lockheed 4200<br>$54 \times 10^6$ Bits |
| Reflectometer | |
| -Wavelength Range | 250 to 2500 nm |
| -Wavelength Resolution ($\Delta\lambda/\lambda$) | $\leq$ 5% |
| -Reflectance Accuracy | 2% |
| -Reflectance Repeatability | 1% |
| Calorimetric Measurements | |
| -Solar Absorptance | Accuracy - 5% |
| -Total Emittance | Accuracy - 5% |

Figure 5 - TCSE Flight Hardware Specifications

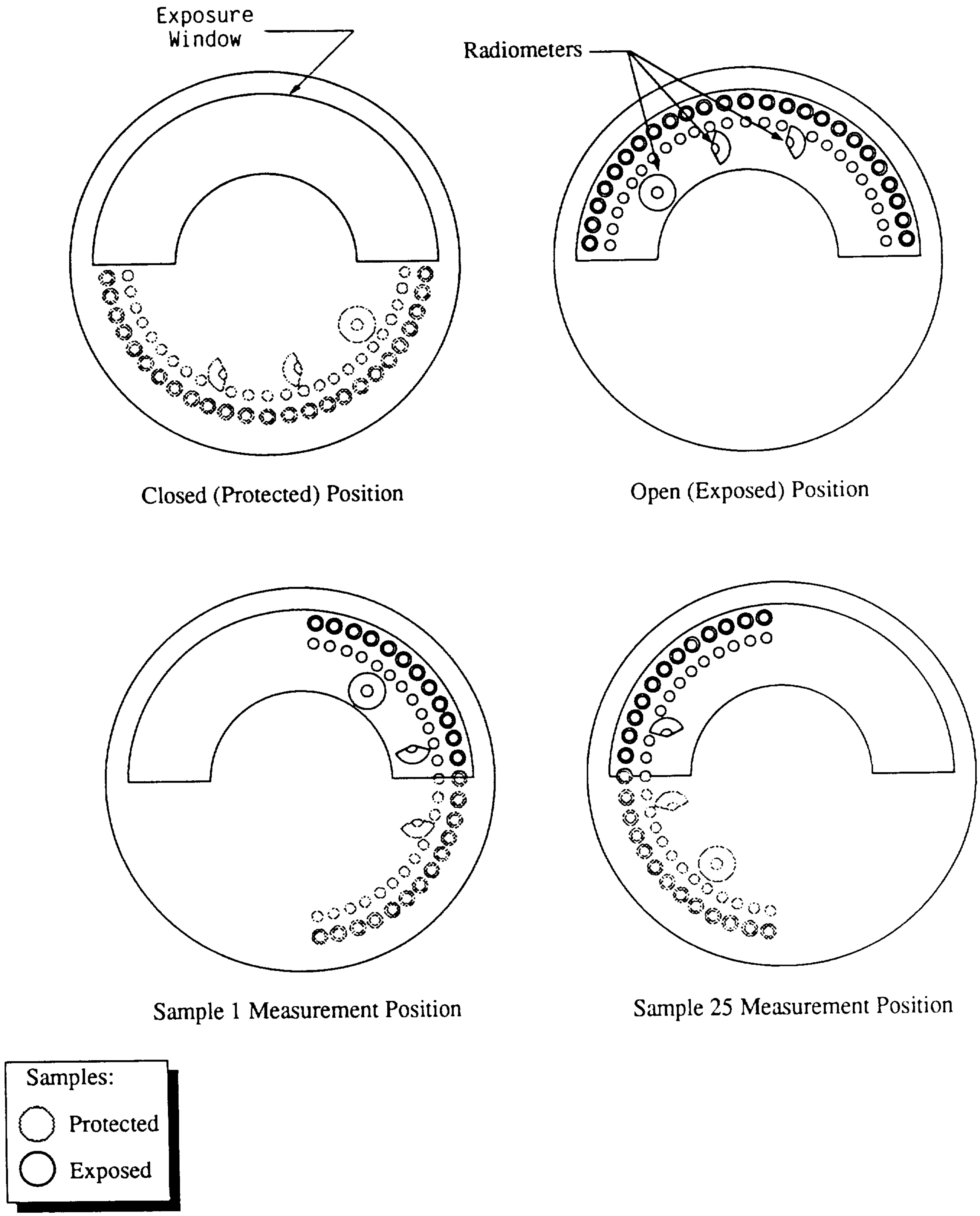



Figure 6 - Carousel Positions

exposure or measurement times of the LDEF mission. The radiometers are also shown, referenced to the flight sample positions. In the exposed condition, the samples experienced space exposure for approximately 23 1/2 hours each earth day. During the protected period of time (approximately 1/2 hour), calorimetric measurements of emittance were made. The protected environment also prevented exposure of the experiment test samples to ground processing and launch contamination.

The carousel subsystem was comprised of the carousel assembly, a stepper motor controlled by the DACS to effect movement of the carousel assembly, a geneva drive assembly consisting of the drive gear and cam, and an emissivity plate. The geneva drive enabled precise repeatable angular rotation such that the same spot on the flight sample was measured. A magnetic sensor on the geneva drive gear sensed a home position to provide the positive indication of a complete movement of one sample position and the locked position of the cam. Pre-flight testing proved the inherent reliability of the geneva drive assembly and the positioning accuracy of each sample. The emissivity plate, combined with calorimeters, was used for the emittance measurements.

#### 2.4.1.1 Radiometers

Three radiometers were used to monitor the irradiance from the sun (direct solar), earth albedo (reflected), and earth IR (emitted) incident on the TCSE. The radiometer data enabled calculation of solar absorptance and total emittance when combined with calorimeter temperature data. The radiometers were

mounted on the carousel and were rotated with the flight samples. The three radiometers used thermopile detectors painted flat black and domed collection optics to measure the energy flux on the TCSE. The direct solar radiometer was installed with a field-of-view equal to the flight samples. A quartz lens was used for the spectral region of 200 to 3000 nm. This region contains over 98 percent of the sun's electromagnetic energy. Like the direct solar radiometer, the earth albedo radiometer used a quartz lens. However, the earth IR radiometer used a germanium lens for the infrared spectrum from 2000 to 20000 nm. The earth albedo and earth IR radiometers were installed with covers such that they had a clear view of only the earth. Data from the radiometers were recorded at minute intervals over a two hour period each day of the active mission during the daily measurement sequence.

2.4.1.2 Calorimeters

Calorimeter sample holders provided a simple method to determine the solar absorptance ( $\alpha_S$ ) and total emittance ( $\varepsilon_T$ ) of the active flight samples. This calorimetric technique measured the inputs to the heat balance equation and calculated solar absorptance and total emittance for the flight samples. The in-space measurements required for this calculation were the temperature of the test sample and the external heat inputs as measured by the irradiance monitors. The calorimeters were designed to isolate the flight sample material thermally from the TCSE to minimize errors caused by radiative and conductive losses. The

TCSE calorimeter design was developed originally by the Goddard Space Flight Center (GSFC) and flown on the ATS-1, ATS-2, and OAO-C satellites.[3]

The calorimetric measurement procedure used on the TCSE is an improvement over past experiments for determining total emittance. Previous experiments determined total emittance when the calorimeter viewed deep space only (i.e., no view of the sun or earth). This orientation was difficult to insure, and the time spent in this orientation was, at times, too short to provide accurate measurements. The TCSE procedure, however, rotated the samples inside the instrument, where they viewed only a heavy black "emissivity" plate. This geometry greatly simplifies the heat balance equation and removes any sun or earth effects.

The calorimeter consisted of three major parts: the sample disk, the inner cup, and the outer cup. Figure 7 illustrates the construction of the calorimeter.

The concept for the three-part calorimeter was for the inner cup to act as a thermal guard for the sample disk. This design featured virtually zero conduction back through the sample holder, low measurable radiative heat transfer to the carousel, and no radiative heat transfer to the sides. The inner cup, or "guard," had the same area and coating as the sample disk to maintain the inner cup temperature close to the temperature of the sample. The thermal capacitance of the inner cup was also as close as possible to that of the sample disk to ensure the guard is effective - even during transient sample temperatures. Kapton film, formed into cylinders, was used to fasten the sample disk

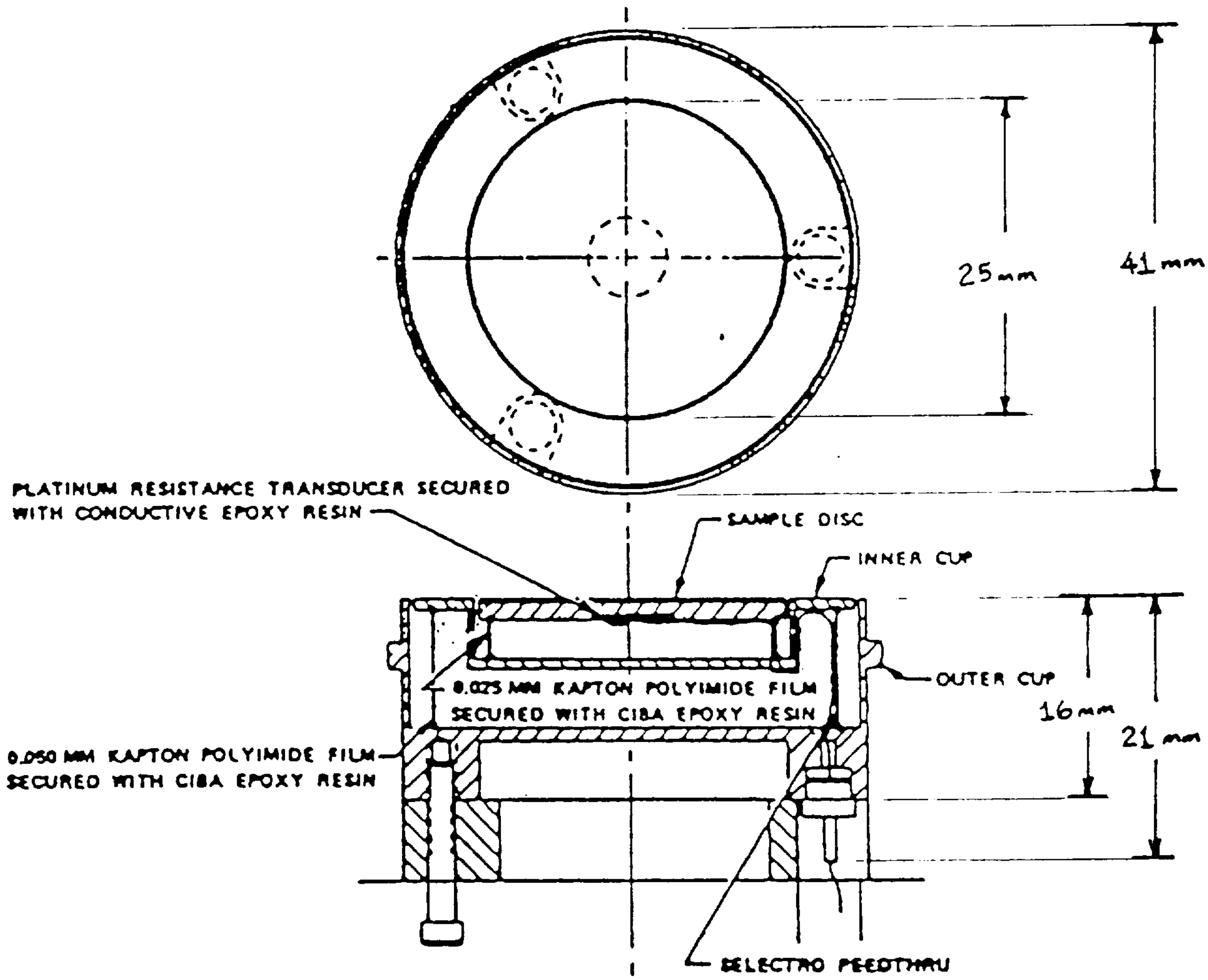



Figure 7 - Calorimeter Sample Holder

to the inner cup and to fasten the inner cup to the outer cup (as illustrated in Figure 7). Crimped double-faced aluminized Mylar sheets were placed inside each cylinder to reduce the radiative heat losses. Vent holes were put in the cylinders and bases of the inner and outer cups, enabling the interior of these cups to vent to the vacuum environment. A solar absorber material was applied to the inner sides of both the inner cup and the outer cup to minimize errors caused by light leaks through the gaps

between the sample, inner cup, and outer cup. A Platinum Resistance Thermometer (PRT) was attached to the underside of each sample disk with thermally conducting silver epoxy to assure good thermal contact with the sample substrate. The Data Acquisition Control System (DACS) monitored the PRT to measure the temperature of the sample disk.

The calorimeter was clamped onto the carousel by the carousel mounting cover. The top of the calorimeter was flush with the top of the carousel.

### 2.4.2 Reflectometer Subsystem

Techniques to evaluate the optical properties of thermal control surfaces have been standardized for the past 25 years and consist of spectral reflectance measurements from 250 to 2500 nm to determine solar absorptance ( $\alpha_S$ ) and total hemispherical emittance ( $\varepsilon_T$ ). Solar absorptance is calculated from the spectral reflectance data. The $\alpha_S$ and $\varepsilon_T$ values determine how the thermal energy is exchanged between a spacecraft and its environment and the resultant temperature values for the spacecraft. The spectral reflectance provides details of the physics of the material and is the best method to calculate solar absorptance.

The TCSE reflectometer optical design, illustrated in Figure 8, is one that is used routinely in the laboratory to measure spectral reflectance. Two light sources, tungsten and deuterium lamps, are used with a scanning prism monochromator with selectable slit widths to provide the monochromatic energy for the

spectral measurement. A 115 mm (4.5 inch) diameter integrating sphere collects both the specularly - and diffusely - reflected light from a wall mounted sample to provide the angularly integrated measurement capability. Figure 9 illustrates the integrating sphere geometry. Kodak Barium Sulfate ($BaSO_4$) was selected for the sphere coating because it was easy to apply, durable enough to withstand the launch environment, and had good optical properties. A UV enhanced silicon photodiode detector and a lead sulfide detector were used with the integrating sphere for the required 250 to 2500 nm spectral range.

### 2.4.3 Data Acquisition and Control System

The TCSE Data Acquisition and Control System (DACS) is shown in Figure 10 and controls all aspects of the TCSE operation. The heart of the DACS is an RCA 1802 CMOS microprocessor with associated memory and input/control ports. A 12-bit analog-to-digital (A-D) converter and analog multiplexer are used to read to measurement data.

A low-power, 25-bit real-time clock was used to keep mission elapsed time. The real-time clock was the only TCSE subsystem that ran continuously from the LDEF "start" signal through battery depletion. The clock subsystem turned on the DACS once each 24 hour day of the active TCSE mission. The DACS, in turn, looked at its internal schedule to determine what functions were to be done that day. At the completion of the day's measurements, the DACS turned itself off, leaving only the real-time clock operating.

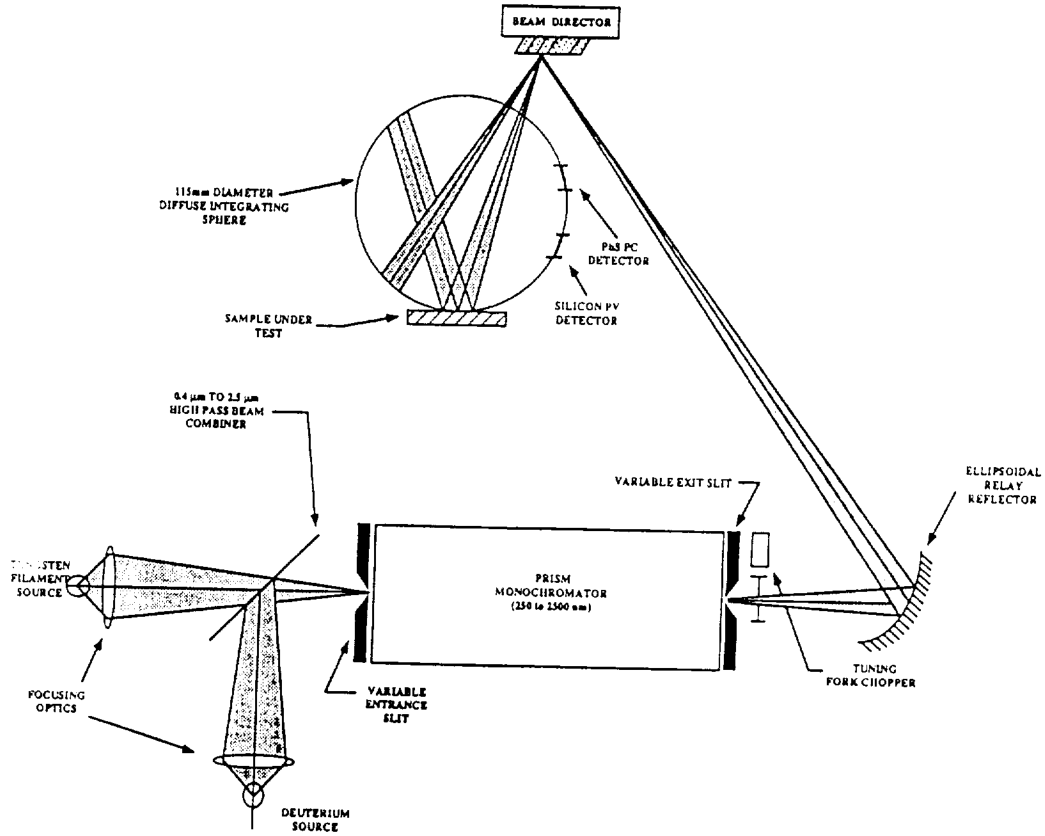



Figure 8 - Reflectometer Optical Schematic

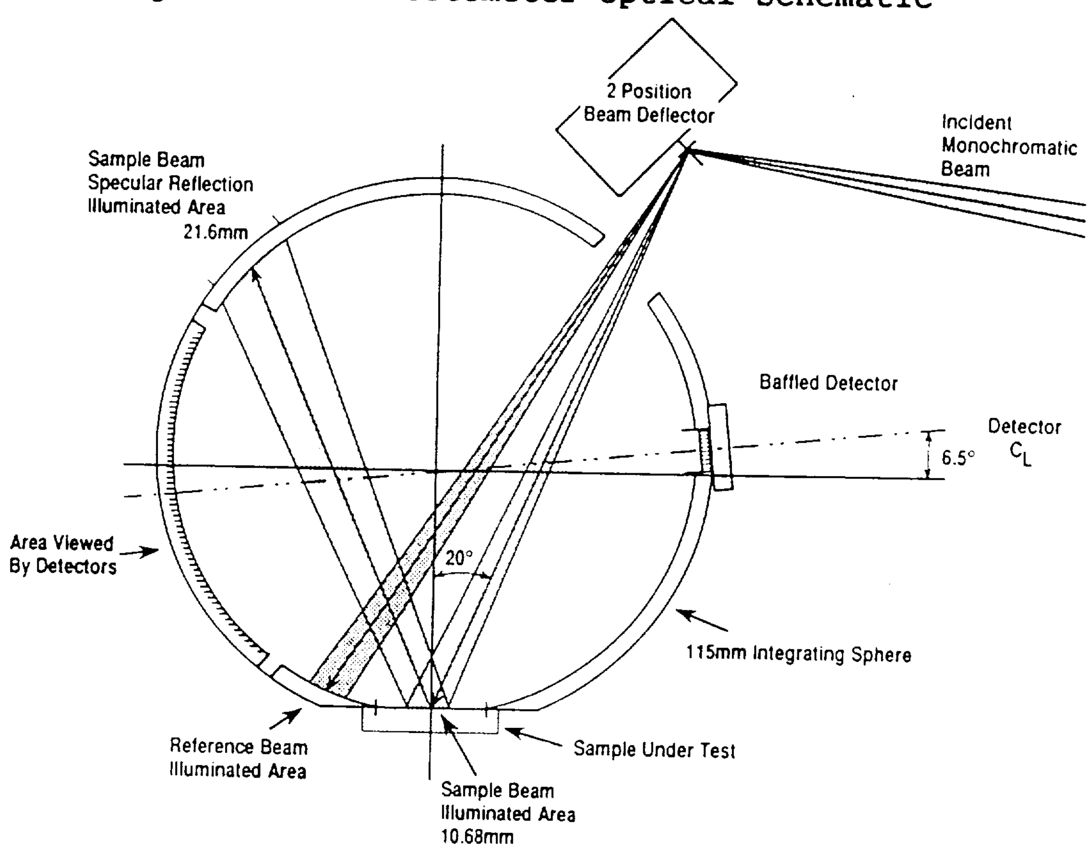



Figure 9 - Integrating Sphere Geometry

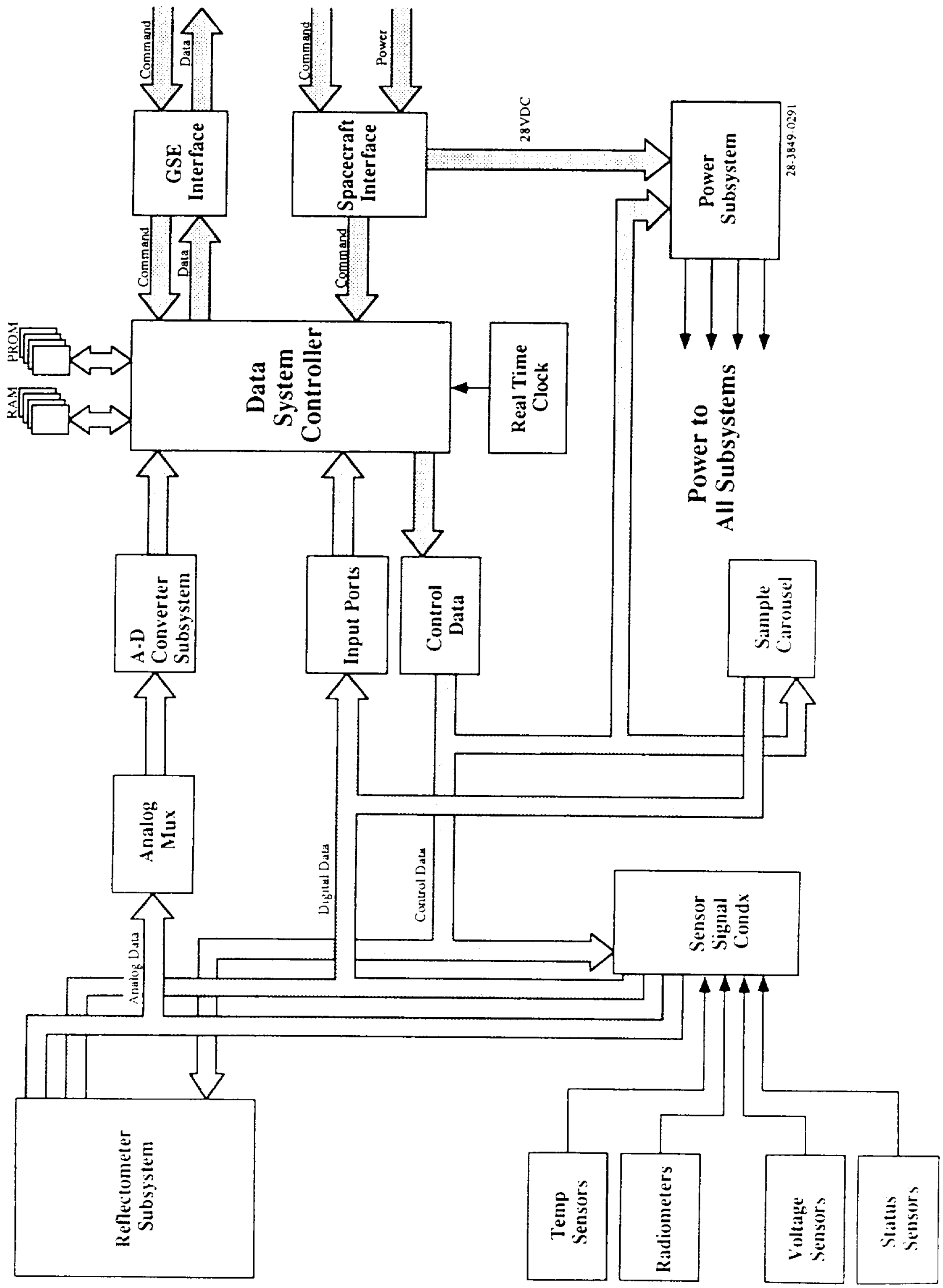



Figure 10 - Data Acquisition and Control System

There were two measurement cycles that the data system controlled, the "daily" measurements and the "reflectance" measurements. The daily measurements were performed once each day after the initial turn-on delay period (refer to Section 3.0). The reflectance measurements were performed at intervals varying from once a week at the beginning of the mission to once a month after three months as defined by the stored program in the data system. The test samples were mounted on a carousel which rotated to the protective position for launch and re-entry, to the exposed position where it resided for most of the mission, and positioned each active sample in turn to the reflectance measuring position (see Figure 6, Section 2.4.1).

In the daily measurement sequence (with the carousel in the exposed position), each of 64 analog channels were sampled once each 64 seconds for 90 minutes. The carousel was then rotated to the protected position and the measurements continued for another 30 minutes. At the end of this cycle, the carousel rotated the samples to the exposed position. The analog channels monitored by the DACS are summarized in Figure 11.

In the reflectance measurement sequence, each sample was positioned in-turn under the integrating sphere twice for reflectance measurements. Each sample, beginning with sample one and continuing through sample 25, was positioned under the integrating sphere and the ultraviolet (UV) portion of the measurements taken. This sequence was then repeated, only in reverse order (sample 25 through sample 1) for the visible and infrared

| COMPONENT | QUANTITY OF SENSORS |
| --- | --- |
| Radiometers | 3 |
| Battery Voltage | 3 |
| PRT's (Calorimeters) | 25 |
| PRT's (Other) | 2 |
| References | 4 |
| Thermistors | 27 |
| Total | 64 |

Figure 11 - Analog Channels Monitored

(IR) measurements. At the completion of this sequence, the carousel rotated the samples to the exposed position.

The reflectometer subsystem is shown in Figure 12. The DACS controls the monochromator wavelength and slit width, selects the appropriate detector and lamp, and measures the reflectance values.

The analog signal processing for the reflectometer is shown in Figure 13. The output from the detector is an AC signal modulated by the 160 Hz chopper and 16 Hz beam director. Figure 14 illustrates the chopped analog signal input to the system multiplexer. This signal is amplified and the 160 Hz modulation is removed using a Phase Sensitive Detector (PSD). The sample

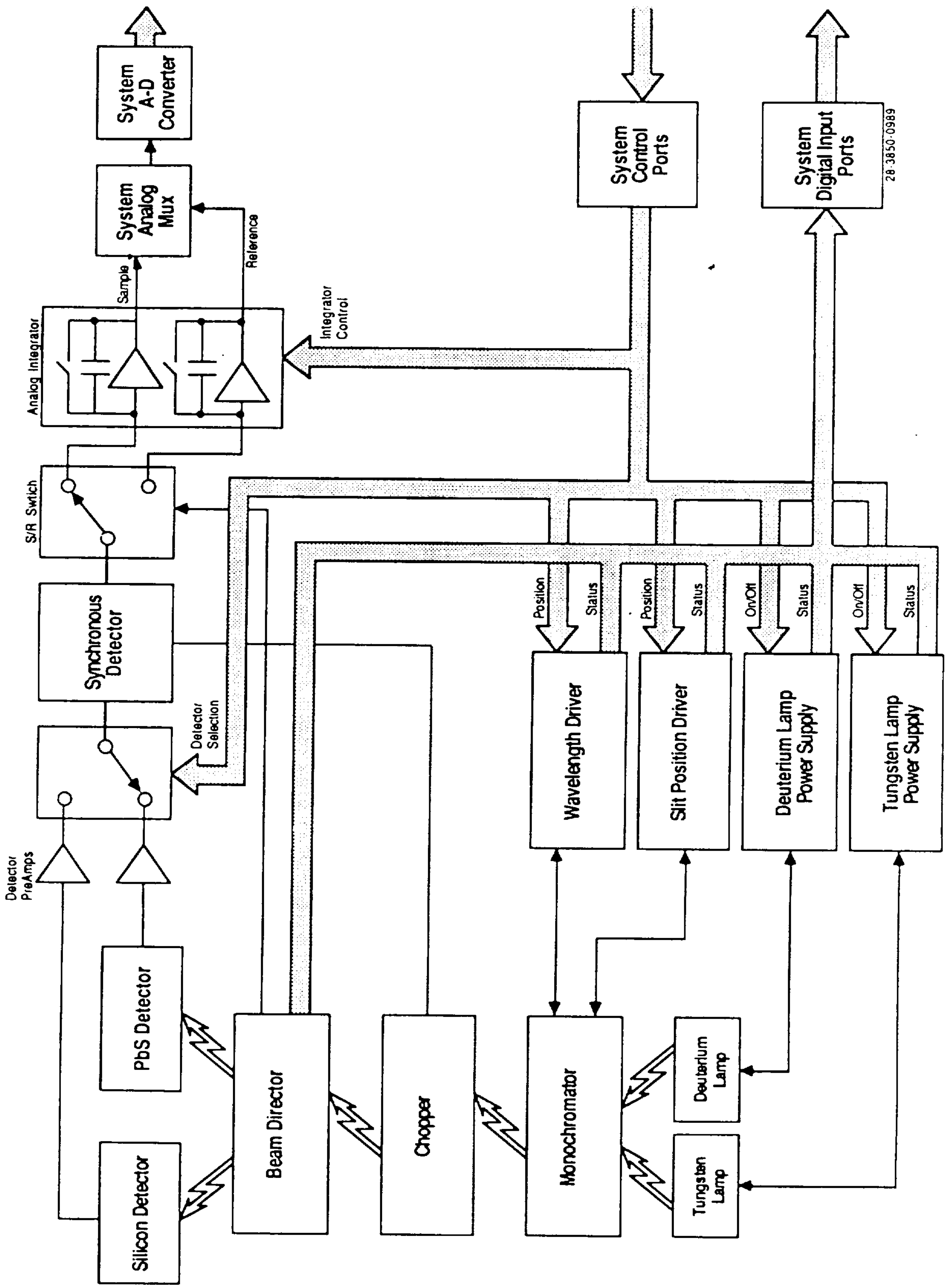



Figure 12 - Integrating Sphere Reflectometer Subsystem

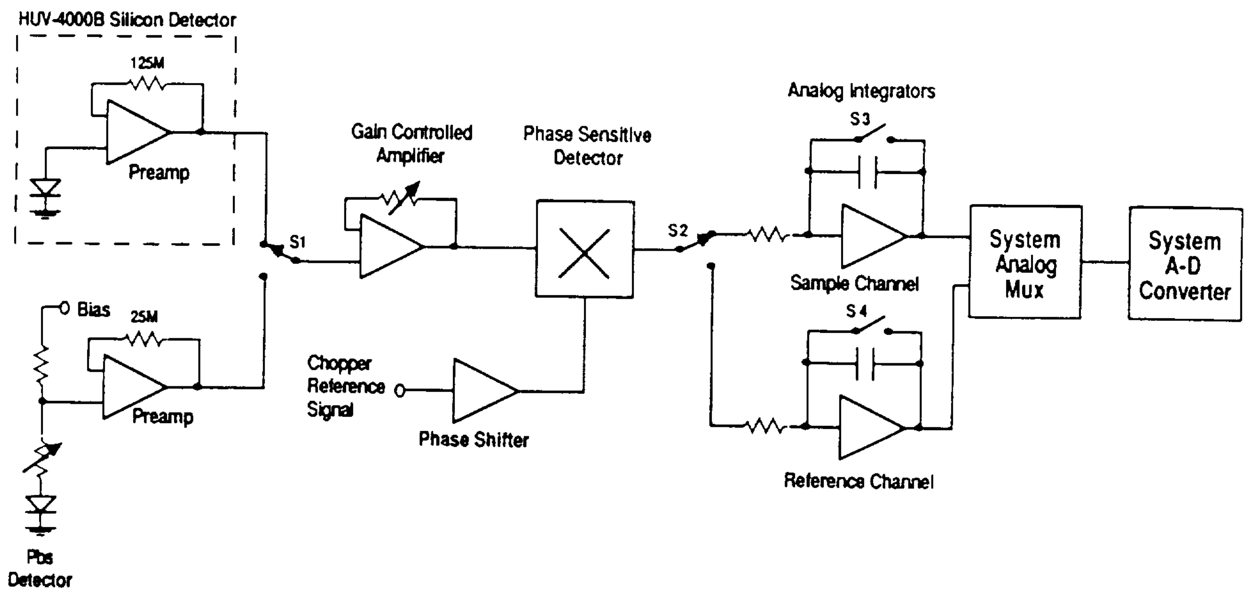



Figure 13 - Reflectometer Analog Signal Processor

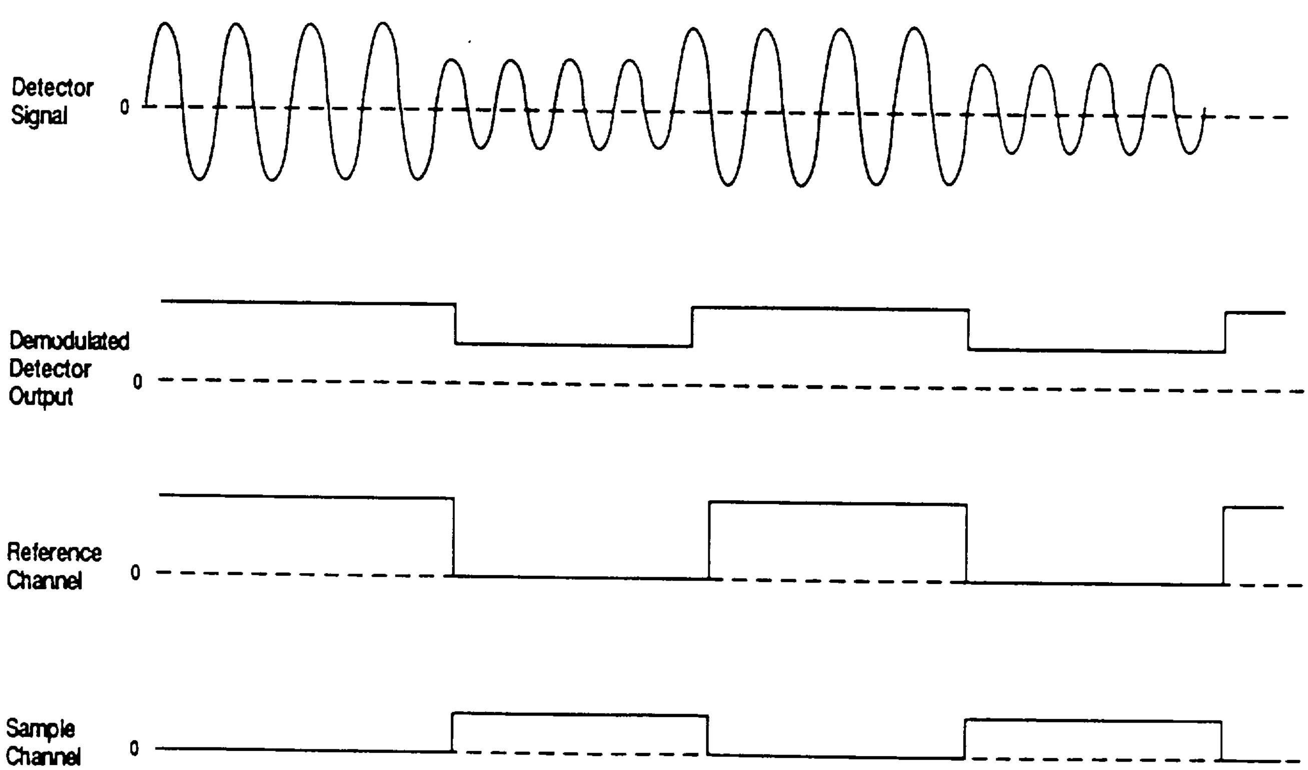



Figure 14 - Reflectometer Analog Signal

and reference portions of the signal selected by the 16 Hz beam director are then separated into two separate channels. Each channel is further processed through active analog integrators providing Multiple Time Averaging (MTA). The output of the integrators is digitized by the system A-D converter and stored in the DACS where further digital MTA can be used as needed to obtain the desired precision. The amplifier gain and the analog integrators are controlled by the DACS. The use of phase sensitive detection techniques - combined with analog and digital multiple time averaging - provides an efficient method to minimize the effects of stray light, drift, offset, $^1/_f$ noise and white noise.[4]

### 2.4.4 Ground Support Equipment

For checkout and test, a set of Ground Support Equipment (GSE) was developed to operate the TCSE, read data from the TCSE and/or recorder, decode these data, and present the data for analysis. The GSE, as shown in Figure 15, consists of a GSE control box, an RCA 1802 MicroMonitor, a tape recorder ground reproduce unit (GRU), and a GSE computer including Cathode Ray Tube (CRT) terminal, disk drive, printer and plotter. The GSE control box simulates the LDEF interface, provides power and power monitoring for ground testing, and provides provisions to input an external clock to speed up ground testing.

The MicroMonitor is an interface to the 1802 Central Processing Unit (CPU) in the flight data system and provides control of the CPU, sets break-points in software, changes and examines

memory data, and runs external test software. The GRU provides ground test control of the flight tape recorder for tape motion, tape erasing, and data playback.

Figure 15 - TCSE Ground Support Equipment



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

The GSE computer system acts as a smart terminal to the MicroMonitor and as a test data storage, decoding, and analysis system. As a smart terminal, the GSE computer can control the MicroMonitor functions and load TCSE test software into the MicroMonitor. The GSE computer can control and test the TCSE tape recorder through the GRU and store TCSE test data on the GSE disks for analysis. In addition, the GSE computer can test the flight recorder by storing data on tape, replaying it and comparing the data. The GSE computer can also directly record TCSE data by "eavesdropping" on data being sent to the flight recorder by TCSE. The GSE computer can decode the packed TCSE data format, analyze the data, print the daily data, and print (or plot) the reflectometer data.

## 3.0 TCSE MISSION SUMMARY

The LDEF was placed in low earth orbit by the Shuttle Challenger on April 7, 1984 (see Figure 16). LDEF was retrieved by the Shuttle on January 12, 1990 after 5 years 10 months in space (see Figure 17). The orbit had a $28.5^{o}$ inclination and an initial altitude of 463 km (250 N mi). The orbit degraded over the 5 year 10 month mission to an altitude of 330 km (178 N mi).

The LDEF was gravity-gradient stabilized and mass loaded so that one end of LDEF always pointed at the earth and one side pointed into the velocity vector or RAM direction (see Figure 18). The LDEF was deployed with the TCSE located on the leading edge (row 9) of LDEF and at the earth end of this row (position A9). In this configuration, the TCSE was facing the RAM direction. The actual LDEF orientation was slightly offset from this planned orientation. The LDEF was rotated about the long axis where row 9 was offset from the RAM direction by about $8^{o}$ [5] (see Figure 19). This LDEF/TCSE orientation and mission duration provided the following exposure environment for the TCSE:

| | |
|---|---|
| Total space exposure | 5 years 10 months |
| Atomic oxygen fluence | $8.0 \times 10^{21}$ atoms/cm$^2$ [6] |
| Solar UV exposure | $1.0 \times 10^{4}$ ESH [7] |
| Thermal cycles | $3.3 \times 10^{4}$ cycles |
| Radiation (at surface) | $3.0 \times 10^{5}$ rads [8] |

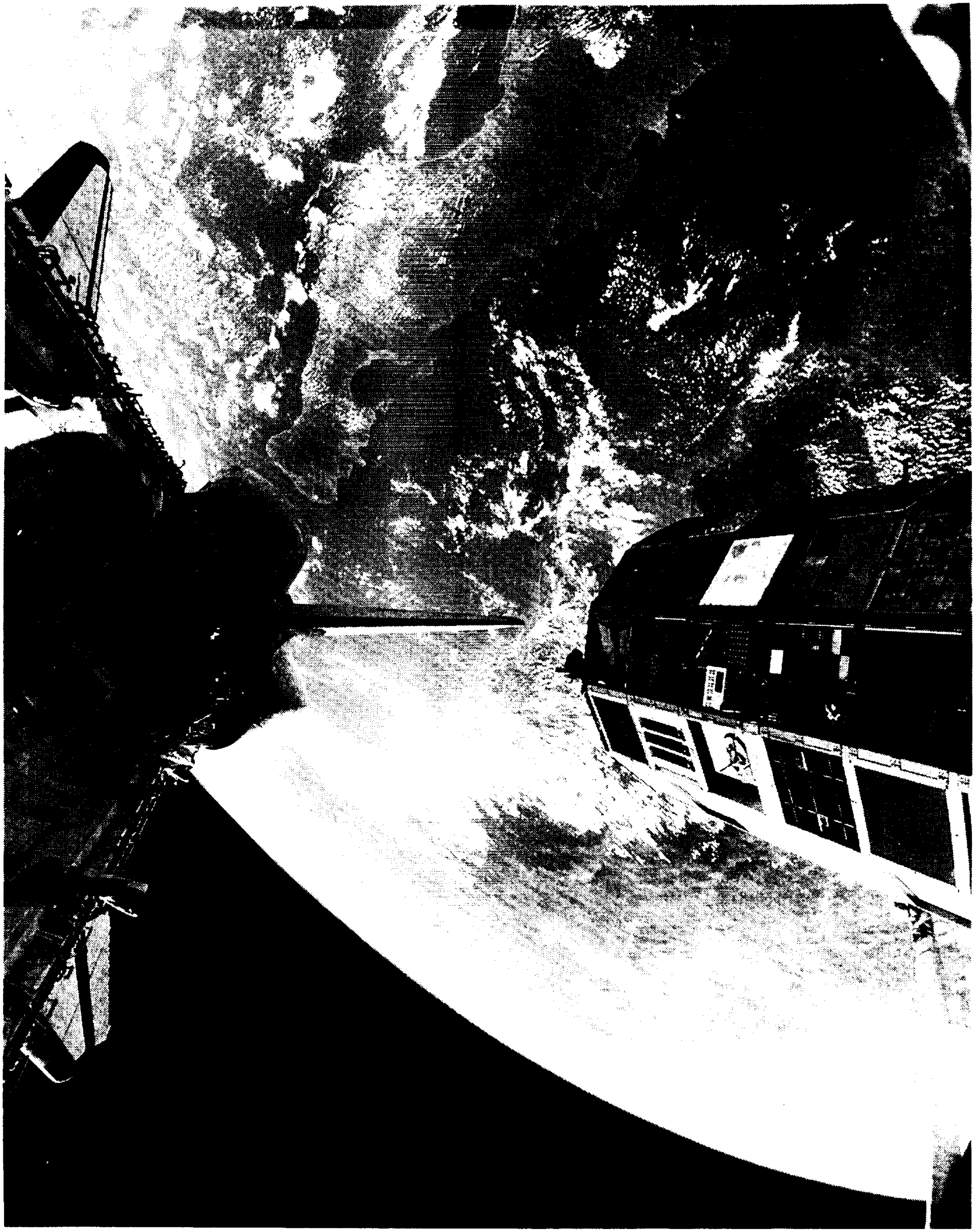


Figure 16 - LDEF Deployment

Figure 17 - LDEF Retrieval

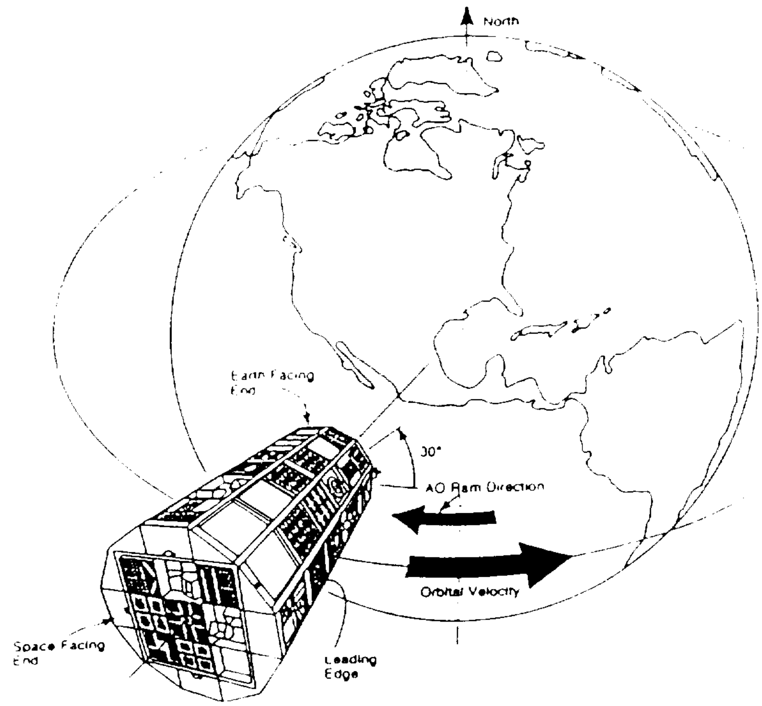



Figure 18 - LDEF Flight Orientation

When the LDEF was placed in orbit by the Shuttle, a "start" signal was sent to the TCSE to engage a relay and turn on the TCSE power. The TCSE was preprogrammed to wait for ten days before exposing the samples to allow the initial outgassing load to diminish.

The TCSE was launched aboard the LDEF with the carousel rotated to the "closed" position to protect the samples from ground processing and the launch environment (see Figure 6).

On mission day 10, the initial daily and reflectance measurements were performed. The carousel was rotated to the open position to expose all test samples. The daily measurements were

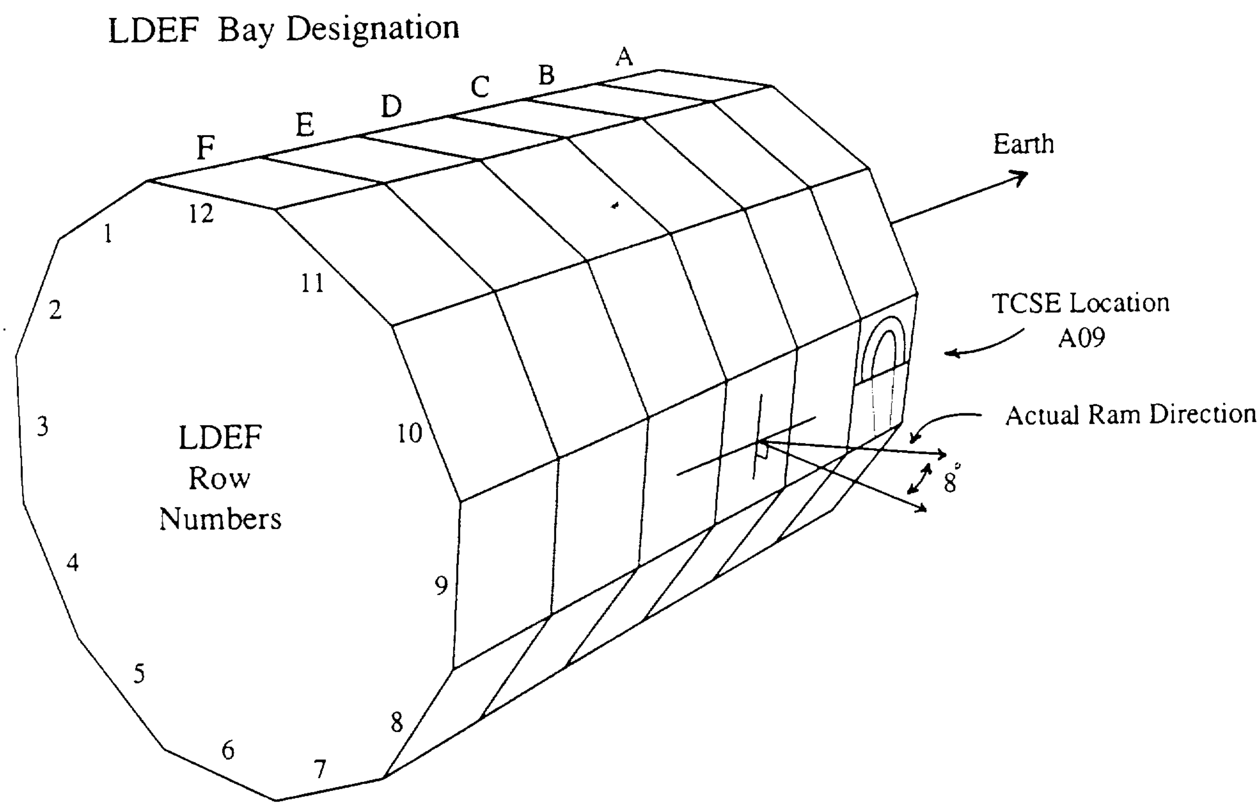



Figure 19 - LDEF RAM Orientation

repeated every day until the TCSE batteries were depleted, which occurred on mission day 582 (19.5 months). The reflectance measurements on the test samples were repeated once a week for four weeks, then once every two weeks for eight weeks, and finally once a month until battery power was expended. The TCSE batteries were sized to provide a 50% margin of additional energy for the nominal 9-12 month LDEF mission. The TCSE mission timeline is summarized in Figure 20.

Mission Time (Days)

| | |
|---|---|
| 0 | - LDEF deployment, TCSE start signal |
| 10 | - Perform initial in-space reflectance and calorimetric measurements |
| 11 (and each day of mission) | - Repeat calorimetric and housekeeping measurements |
| 17 * | - Repeat reflectance measurements<br>* Reflectance measurements were made once every week for the first four weeks, once every two weeks for the next eight weeks, and once a month thereafter. |
| 582 | - Batteries were depleted and the TCSE systems shut down |

Figure 20 - TCSE Mission Timeline Summary

As discussed previously, the TCSE operated for 582 days before battery depletion. The battery power was finally expended while the sample carousel was being rotated. This left the carousel in a partially closed position. Figure 21 is a photograph taken during the LDEF retrieval operations showing where the carousel rotation stopped. This carousel position caused 35 of the samples to be exposed for the complete LDEF mission (69.2 months), and 14 exposed for only 582 days (19.5 months) and therefore protected from the space environment for the subsequent four years.

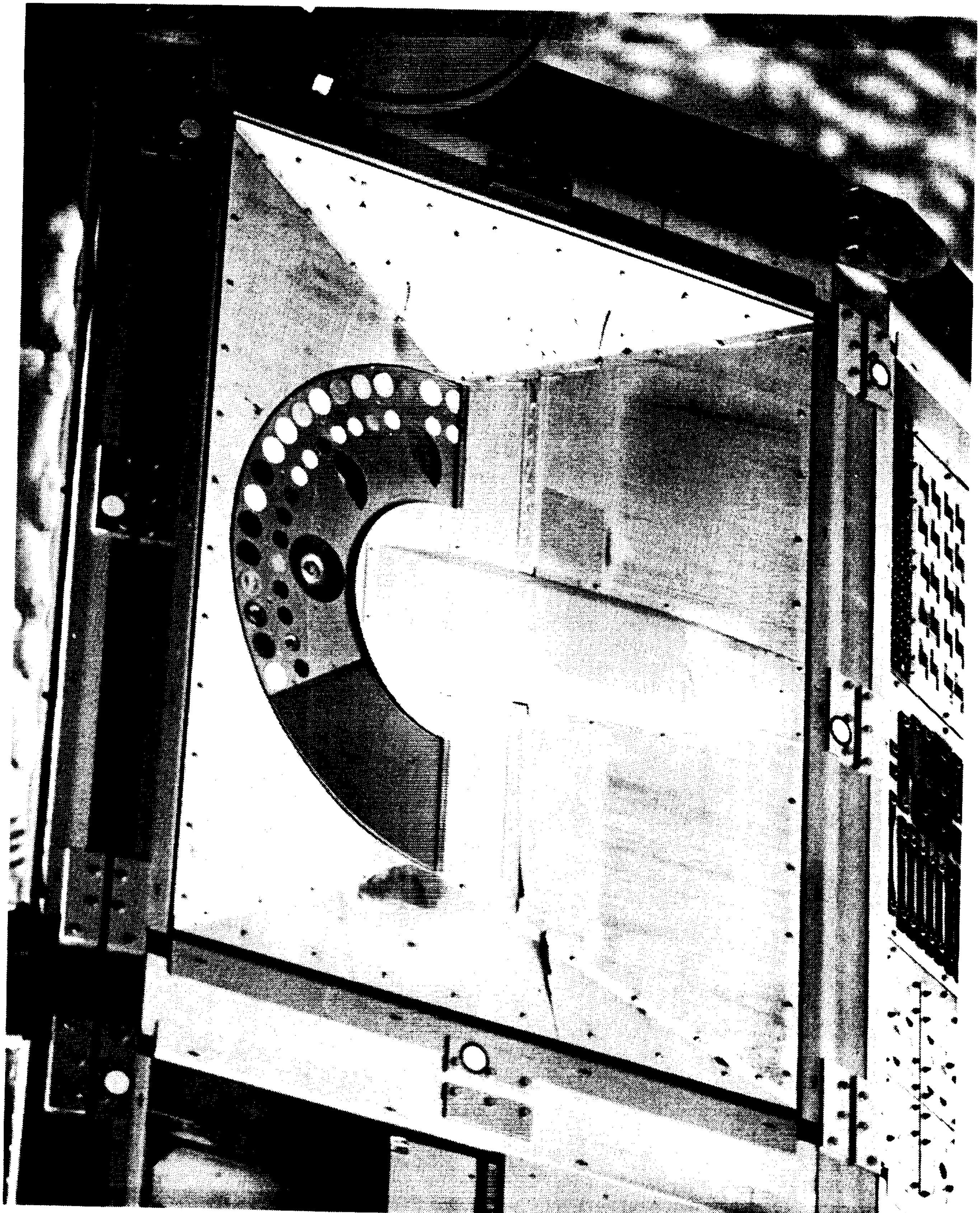


Figure 21 - TCSE Condition at LDEF Retrieval

### 3.1 LDEF/TCSE Deintegration Activities

On February 1, 1990, the LDEF was removed from the Shuttle Columbia at Kennedy Space Center (KSC) and transferred to a payload processing room for the initial close-up inspection. Special Investigative Groups (SIGs), established by NASA to ensure all LDEF relevant data were collectively archived for future analyses, began their investigations.

The Micrometeoroid and Debris Special Investigation Group (M&D SIG) conducted an initial inspection of the entire LDEF structure on February 20-23, 1990 while all 57 experiments were mounted to the structure. From February 23 through April 19, 1990, detailed examination and photo documentation of all experiments was conducted by the M&D SIG team as each experiment was removed from the LDEF structure. The TCSE deintegration occurred in early March. This team documented all craters greater than 0.5 mm in diameter and all penetration holes greater than 0.3 mm in diameter. The size, type, location and feature characteristics of all documented impacts were recorded.[9] Stereo-microscope imaging systems were fitted with color Charge-Coupled Device (CCD) cameras, 35 mm cameras, and fiber optic cold-light illuminators for viewing. Data were recorded on optical-disk cartridges and archived in the Johnson Space Center (JSC) Curatorial Facility Data Vault. A summary of these results is presented in Figure 22.

One penetration occurred on the TCSE front cover. The M&D published report states, "The largest documented feature was a 2.5 mm diameter impact in the silver Teflon cover. This impact

| Impact Dimensions | Mounting Shims | Clamps,Bolts Flanges | Tray Surfaces | Experiment Surfaces |
|---|---|---|---|---|
| < 0.5 mm* | 6 | 0 | 0 | 543 |
| > 0.5 mm | 5 | 3 | 3 | 39 |
| Totals | 11 | 3 | 3 | 582 |

* Impacts less than 0.5 mm were counted, not photo documented.
Impacts less than 0.1 mm were not counted.

Figure 22 - M&D SIG TCSE Feature Summary

delaminated a considerable amount of the Teflon blanket and exposed the silver backing to oxygen erosion."

Following the M&D SIG investigation, the TCSE was shipped back to MSFC for data analysis. At MSFC, the TCSE covers were removed and the interior of the instrument visually and photographically inspected.

Data from the LDEF, and the TCSE, soon became the focus of other space programs. In March 1990, during the early phase of data analysis, the Hubble Space Telescope (HST) program office requested information from the MSFC and TCSE investigators regarding the space environmental effects on silver Teflon. This material is installed on the HST 2.7 m (9 feet) aft shroud external surfaces and questions had arisen about its durability for extended space missions, especially with the visual appearance of the LDEF silver Teflon surfaces. To support this inquiry and respond in a timely fashion for the planned April 1990 launch of the HST, portable instruments were used to measure the optical properties of the silver Teflon surfaces on TCSE and other MSFC

experiments. The TCSE and other MSFC experiments were deintegrated earlier than planned in the LDEF post-mission processing so additional analyses could be performed.

The results of these studies determined that the HST thermal system had sufficient margins to function with the degradation observed on the LDEF mission. This cooperative effort exemplifies the significance of the TCSE and LDEF data for future long duration space missions.

## 4.0 TCSE SYSTEM PERFORMANCE

The TCSE flight hardware system performed very well during the LDEF mission. A few anomalies have been detected in post-flight data analysis, inspection, and functional tests.

The systems analyses performed is only the initial effort required to fully characterize the effects of the long term space exposure. Performance of the TCSE system and operational anomalies are described in this section.

### 4.1 Recorder

The TCSE data system utilized a Lockheed Electronics Company (LEC) model MTM four-track tape recorder to store the flight data. The flight recorder was removed and handcarried to the Lockheed Electronics Company for transcription of the flight data and an analysis of the condition of the recorder.[10]

Upon opening the recorder it was determined that a relay in the track switching circuit had failed with the wiper on one set of contacts stuck in an in-between state. This condition prevented the relay from receiving additional track switching commands and resulted in the overwriting of one of the three tracks of data collected by the TCSE. The LEC engineers manually energized the relay coil and the relay contact latched properly. This relay and the complete recorder system performed within specification for the check-out tests and flight data playback.

The MTM tape recorder is a four-track unit that records tracks 1 and 3 in the forward direction and tracks 2 and 4 in the reverse direction. At the completion of the TCSE mission, the

recorder stopped with the tape positioned near the end of track 1. However, it was determined that track 3 data was written over track 1 data. Because the MTM recorder uses a saturation recording method, track 3 data was recovered. Track 2 data was recovered with no problems. Some track 1 data was apparent in gaps between track 3 data blocks and may be recoverable. This failure and its cause will be investigated further in later studies. The LEC and NASA/LaRC personnel provided a very valuable service in this analysis and in the recovery of the TCSE flight data.

The recovered TCSE flight data was decoded and separated into data sets. By analyzing the clock data in each data set, it was determined that the TCSE operated for 582 days (19.5 months) after LDEF deployment. Data were recovered for the last 421 days of this operational period. The overwriting of track 1 data by the recorder resulted in the loss of data for the first 161 days of the TCSE mission. The recovered data included eleven reflectometry data sets and 421 daily data sets.

4.2 <u>Reflectometer</u>

Data reduced from the flight recorder indicate the reflectometer performed very well. In Figure 23, the measurement repeatability over several months is observed to be generally within 1 to 2 percent. This excellent performance indicates that measured changes by the TCSE reflectometer were accurate and did occur.

The post-flight analyses of the TCSE reflectometer consisted of visual inspections and functional tests. Visual inspections

of the reflectometer components revealed no unusual surface features, i.e., discoloration, deformation, aging, etc. The integrating sphere coating appeared to be intact. There was no evidence of mechanical misalignment after the extended mission. Functional tests were conducted on the reflectometer subsystem components - including the tungsten and deuterium lamps and the monochromator wavelength and slit stepper motors - to determine their status after the prolonged space exposure. A functional test was also conducted on the complete reflectometer subsystem. Functional tests on components were performed first to verify function and check for start-up power transients. System level tests followed to verify system performance.[11]

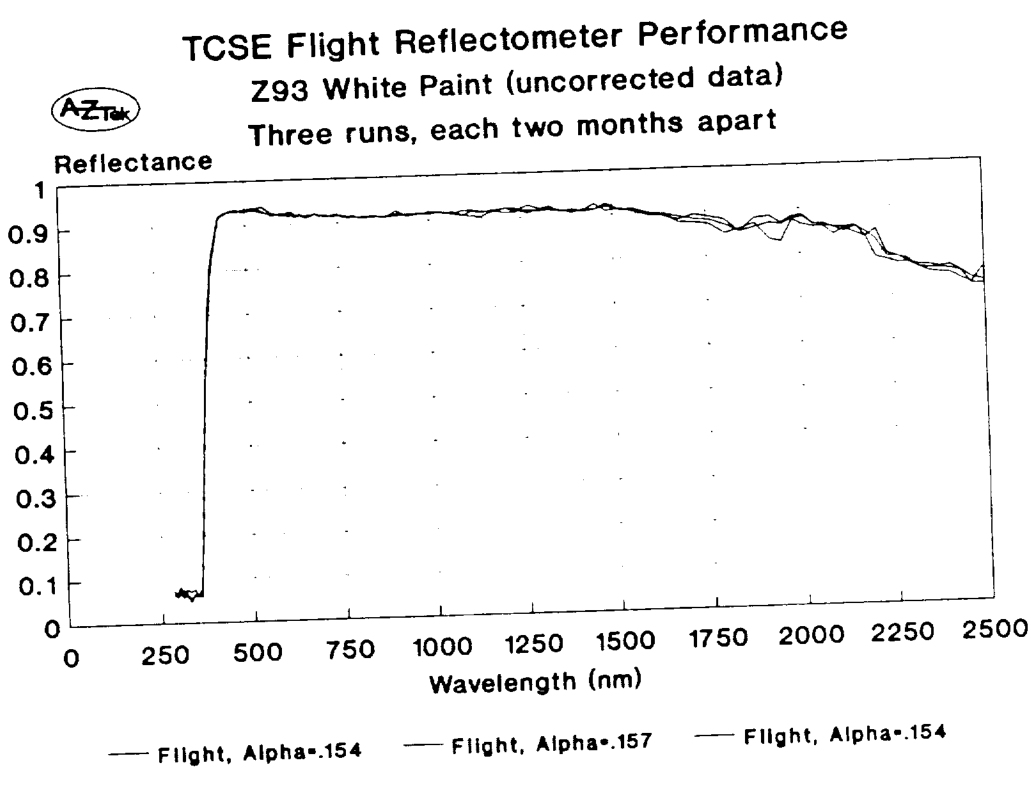



Figure 23 - Z93 Flight Reflectometer Performance

The component functional test results of the two lamps and power supplies were nominal. The lamps and power supplies responded to computer control as designed. There were no measured atypical power transients. The tungsten lamp irradiated normally at power on, and a visual check in the integrating sphere verified the visible spectrum between 500 and 700 nm. The deuterium lamp irradiance appeared slightly unstable due to flickering of the lamp arc. No visual inspection was possible of the UV energy from the monochromator.

Functional tests of the two stepper motors on the monochromator were nominal. No adverse power transients were recorded at power on and the stepper motors responded to computer control.

A functional test of the reflectometer subsystem followed the component level functional tests to determine overall system health. The functional test measured reflectance of ground control samples. The reflectometer subsystem operated normally.

The reflectance data from this functional test was decoded and analyzed to determine the condition of the reflectometer subsystem. The near infrared data from 2500 nm to about 600 nm looks reasonable with signal levels on the same order as preflight values (even a little higher above 1500 nm); however, a little more noise is evident in the data. From 600 nm to 400 nm, signal levels are significantly lower and noisier but some data is usable. Below 380 nm, where the deuterium lamp is used, the data are suspect. Signal levels appear to be high enough to provide good measurements but the data do not agree with ground

measurements. For example, the white paint test samples should have low reflectances (<10%) below 380 nm but very few points are in that range. The data in the lower visible and UV suggest a wavelength shift in the measurements. These results will require additional study in later subsystem tests. Figures 24-26 are examples of the post-flight measurements made with the TCSE reflectometer. Several data points in the UV were well over 100% and were omitted from these curves.

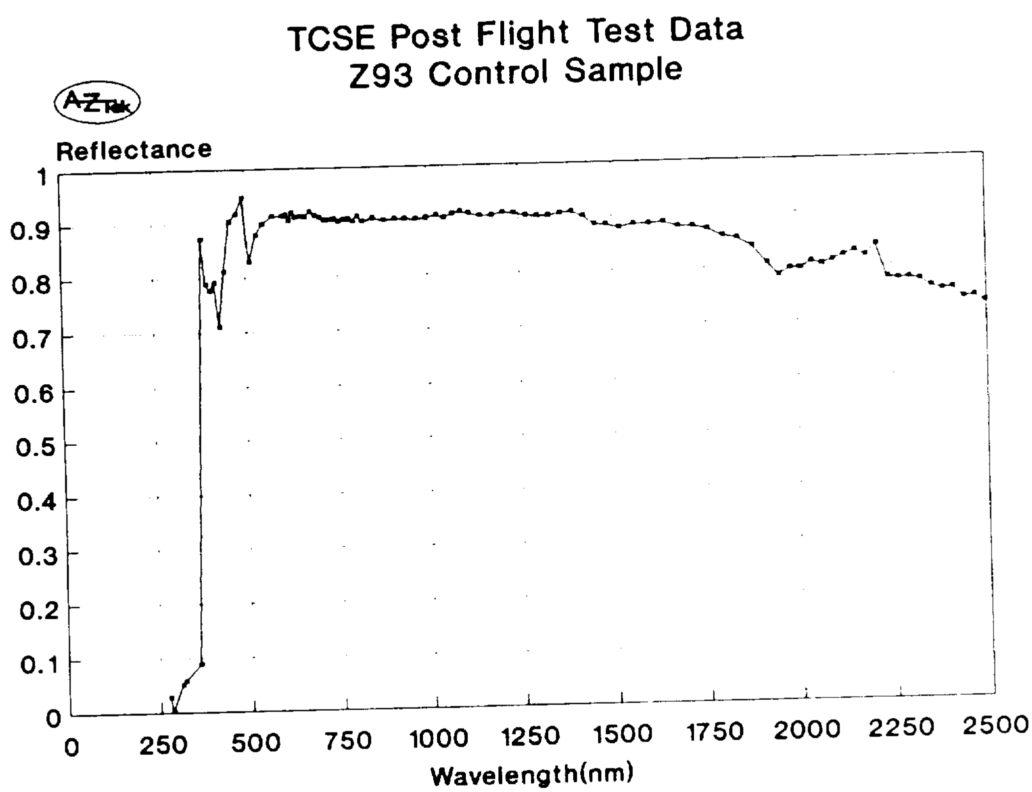



Figure 24 - Z93 Post-Flight Functional Test Data

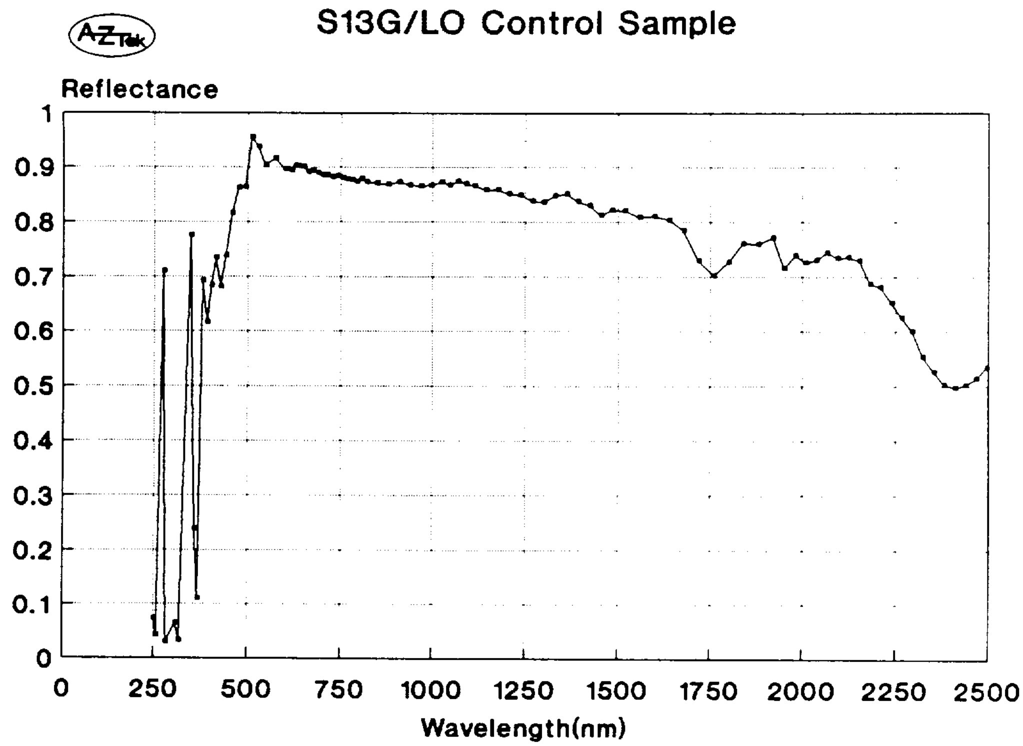



Figure 25 - S13G/LO Post-Flight Functional Test Data

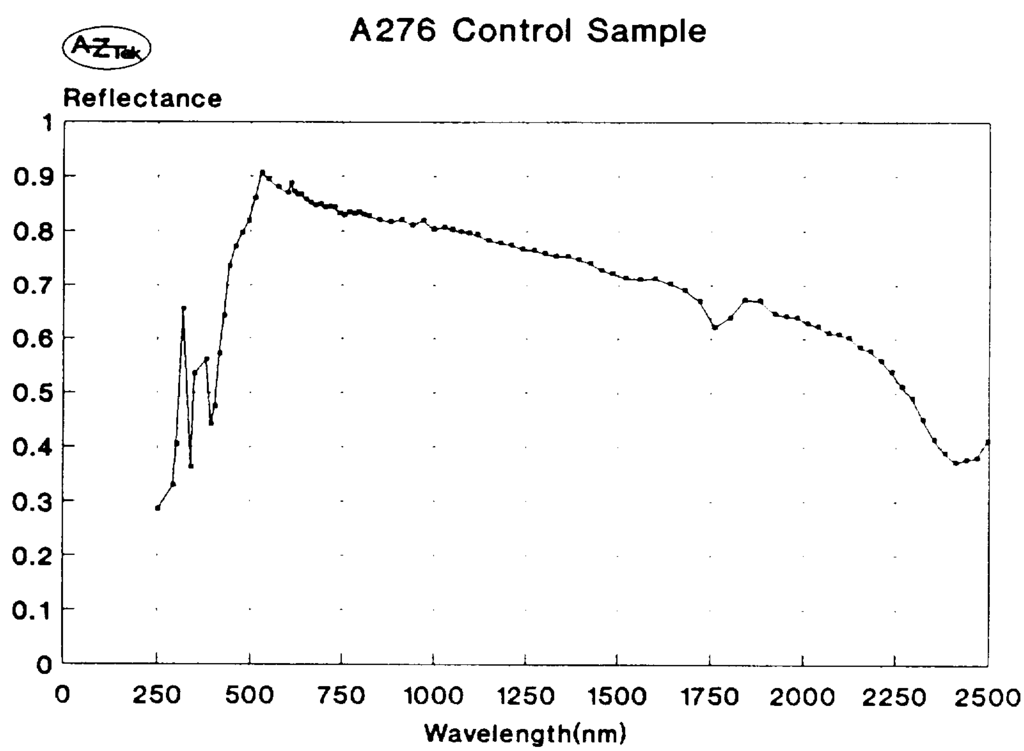



Figure 26 - A276 Post-Flight Functional Test Data

4.3 Batteries

Four standard lithium range safety batteries were used to power the TCSE. These batteries were developed for the Shuttle Solid Rocket Booster (SRB) range safety system. The batteries were selected based on their high energy density and ready availability at MSFC. These batteries had a predicted life of greater than 15 months from calculated power requirements, which was more than adequate for the planned 9-12 month LDEF mission. Each battery was rated at 28 Volts Direct Current (VDC) and self-contained in a two-part Nylafil case. An ethylene propylene o-ring was used to seal the case. Due to the characteristics of the lithium electrolyte, each cell was designed to vent into the cavity when overpressurization occurred. During an overpressurization condition, a small diaphragm on each cell balloons out and is pricked by a metal pin to relieve pressure. The escaping gas is then contained within the Nylafil case by the ethylene propylene o-ring.

During the initial post-flight analysis, a noticeable odor was evident during TCSE deintegration at the MSFC. The source of odor from inside the TCSE was identified as the electrolyte from the lithium batteries. The batteries were removed from the TCSE and bagged. Each of the four batteries in the TCSE had this odor. One battery was cut open to check the cell diaphragms and the battery o-ring. All cells had vented, noted by punctured diaphragms. In addition, the battery o-ring was checked for compression sets, and was measured to be 100 percent (see Figure 27). Since the compression set on the o-ring was 100 percent,

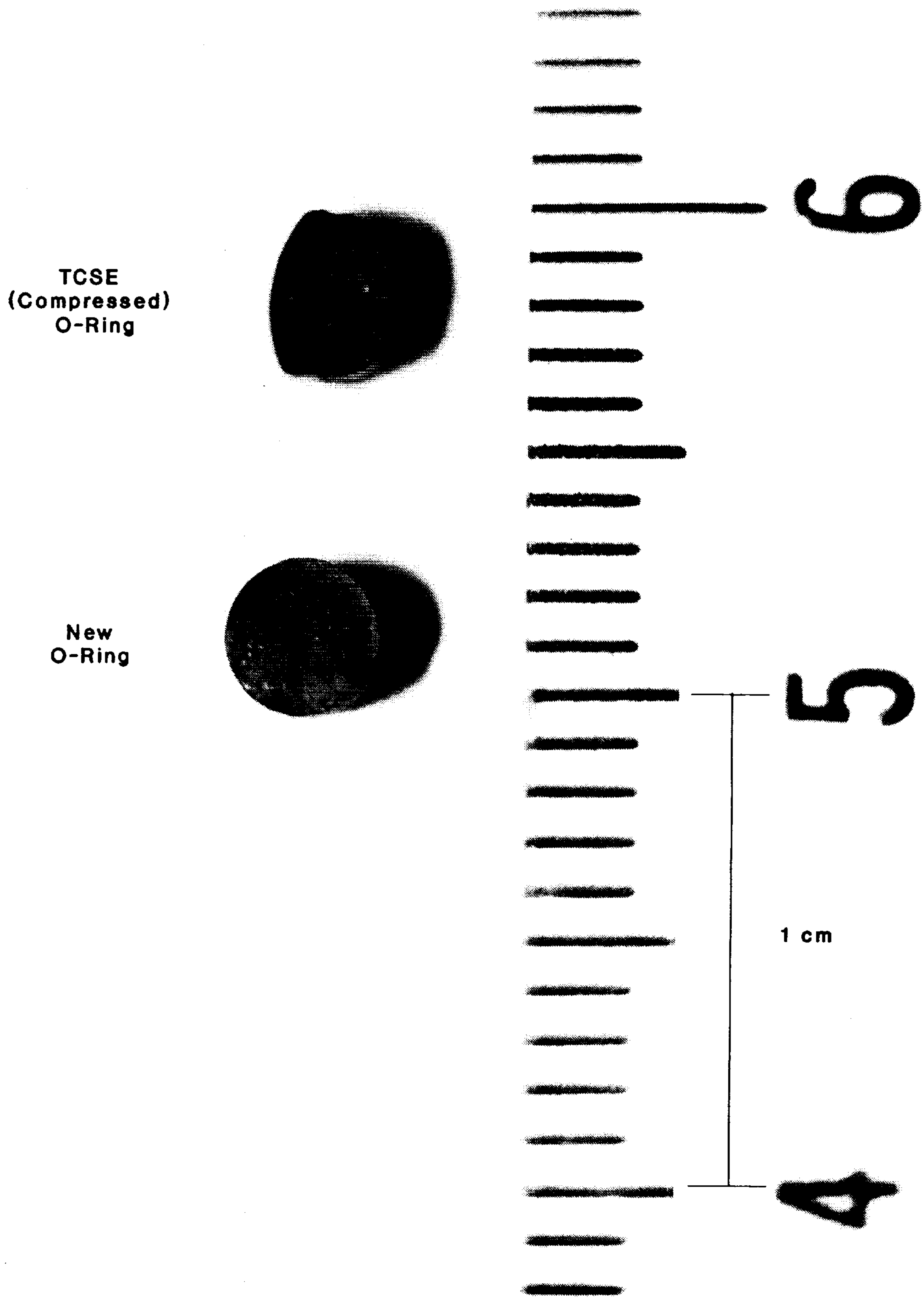



Figure 27 - Battery O-Ring Deformation

electrolyte gas was able to escape from the batteries. The o-ring did not operate as designed.

Post-flight data reduction revealed the battery temperature ranged from 13 to 27°C (refer to Section 4.6). This temperature range permitted most of the battery energy to be utilized and enabled a long-life mission. Battery voltage ranged from a nominal 36 Volts DC near mission initiation down to 25 Volts DC at battery depletion. Figures 28 and 29 illustrate measured battery voltages during the TCSE mission. The battery voltage was measured at very low current draw which represented a nearly open circuit condition.

Battery life extended through 582 mission days (19.5 months), well beyond the intended mission time of 12 months, and beyond the anticipated battery lifetime of 15 - 18 months.

## 4.4 Sample Carousel

The carousel subsystem provided protection for the samples during launch and positioned the active flight samples under the reflectometer integrating sphere for measurement.

Post-flight analyses of the recorded TCSE data show that the carousel subsystem operated as designed most of the time, but indicate an intermittent rotational problem. From the recorded flight data, the carousel drive mechanism experienced some difficulty in rotating reliably from sample position 25 to sample 24 during the reflectance measurement. This difficulty appeared to be more prominent towards the end of the useful battery life. This problem was investigated briefly during a post-flight func-

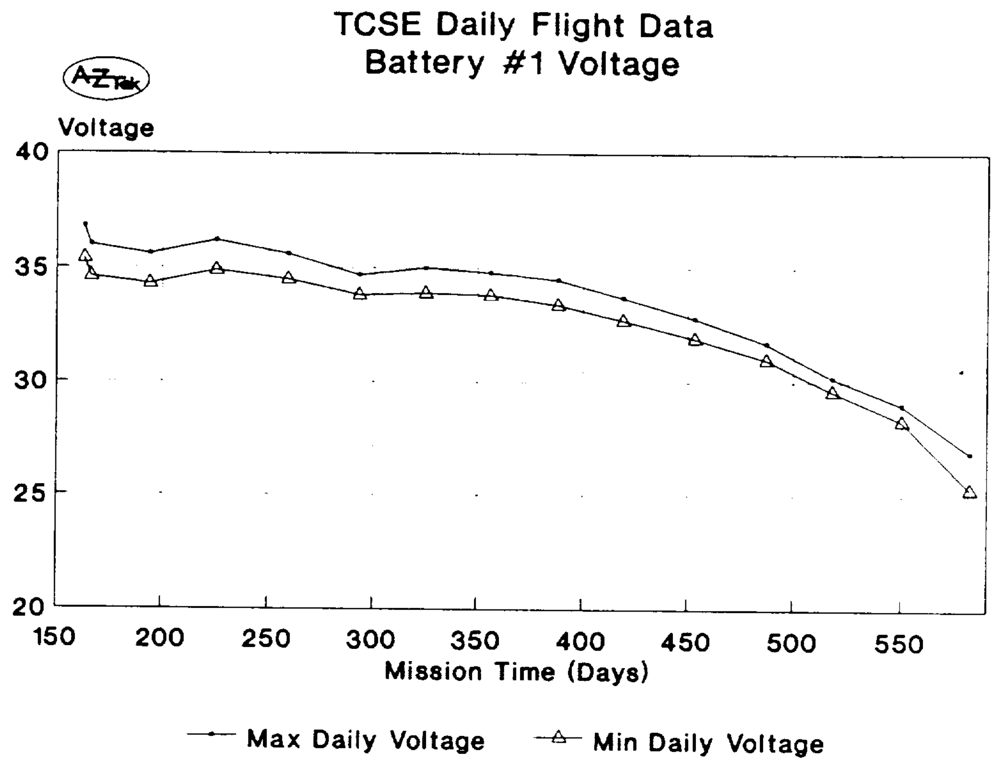



Figure 28 - Battery Voltage #1

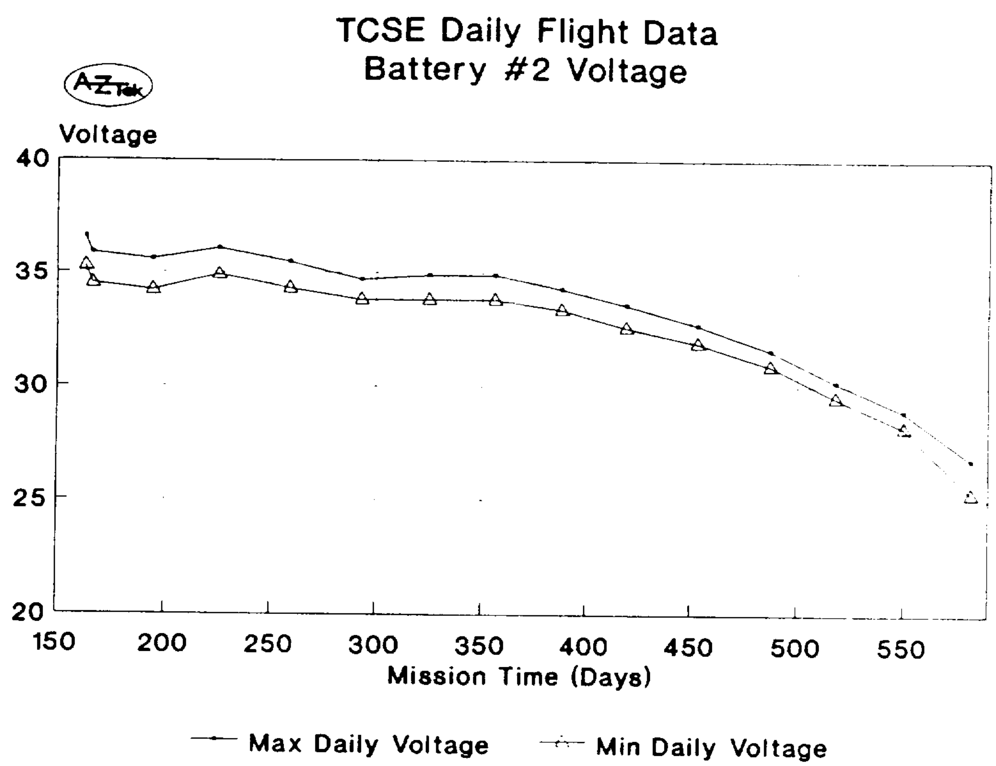



Figure 29 - Battery Voltage #2

tional check-out test.[11] Attempts were made to simulate the problem by adjusting the battery supply voltage (and energy levels) from 28 to 21 volts as well as energizing the lamps and other components of the reflectometer subsystem to simulate increased energy requirements on the power system. Unfortunately, the carousel rotation anomaly could not be reproduced in these initial ground tests. Other conditions of the space environment (i.e., thermal, vacuum, etc.) were not simulated which may have synergistic effects on the carousel drive motor operation. This remains an open item for later resolution. All other post-flight carousel functional tests were nominal.

A post-flight visual inspection of the radiometers revealed some minor debris or micrometeoroid impacts on the lenses. It is unknown if these impacts were significant enough to have changed their response to the energy flux.

## 4.5 Data Acquisition and Control System

The initial analysis of the TCSE flight data shows that the DACS performed very well during the active TCSE mission. Post-flight functional tests show that the DACS remains functional after the extended dormant period in space.[11]

The clock data on each recorded data buffer showed that the DACS started a measurement sequence precisely on 24 hour increments as measured by the TCSE clock. The daily sequence was repeated for 582 days until the batteries were depleted. Because of the recorder malfunction, only 421 days of data were recovered.

The data from the post-flight functional tests were analyzed to check the condition of the analog measurement system. There were five reference channels among the 64 analog channels. These provided a calibration for thermistors and platinum thermometers on the calorimeters. The values of these readings depend on the current sources in the measurement circuits, the precision reference resistors, the scaling amplifiers, and the A-D converter. For four of these reference channels, the range of values measured over the two hour test exactly matched the in-flight values. The fifth measurement was off one count in 900 or just over 0.1%. This test verified that the analog measurement system remains within design specifications.

Only one anomaly has been observed in the DACS operation. The 25th clock bit appeared to be set to a logical "1" too early and remained in that condition throughout the mission. This bit was also set to "1" during the post-flight testing -- indicating a failure. This condition was not a problem in the data analysis because the sequential nature of the data allowed recovery of the full clock data.

## 4.6 Thermal

The thermal design requirements for the TCSE mission, defined at the TCSE Critical Design Review, are given in Figure 30. Scenarios for zero solar input (cold case or minimum temperatures) and predicted solar input (hot case or maximum temperatures) were used as specified in the LDEF Users Handbook[12] to determine the thermal environment that the TCSE could expect

during its mission. Some yaw (x-axis) instability was expected for this gravity-gradient stabilized satellite and was considered in the thermal analysis. However, little yaw occurred, and the satellite proved to be very stable--resulting in moderate temperatures.

| Component | Allowable Temp. Limit | | Predicted Temp. Limit | |
|---|---|---|---|---|
| | Min (°C) | Max (°C) | Min (°C) | Max (°C) |
| Integrating Sphere | -50 | 60 | -25 | 41 |
| Batteries | -30 | 60 | -23 | 43 |
| Electronics (DACS) | -40 | 70 | -27 | 41 |
| Emissivity Plate | | | -25 | 40 |

Figure 30 - Allowable and Predicted Thermal Data

The TCSE used 2 mil silver Teflon as the outside (exposed) surface coating and black painted aluminum for inside and back surfaces. The top cover (shroud) was thermally isolated from the TCSE structure. The TCSE was thermally coupled to the massive LDEF structure for passive thermal control, and was dependent upon this environment for thermal stability.

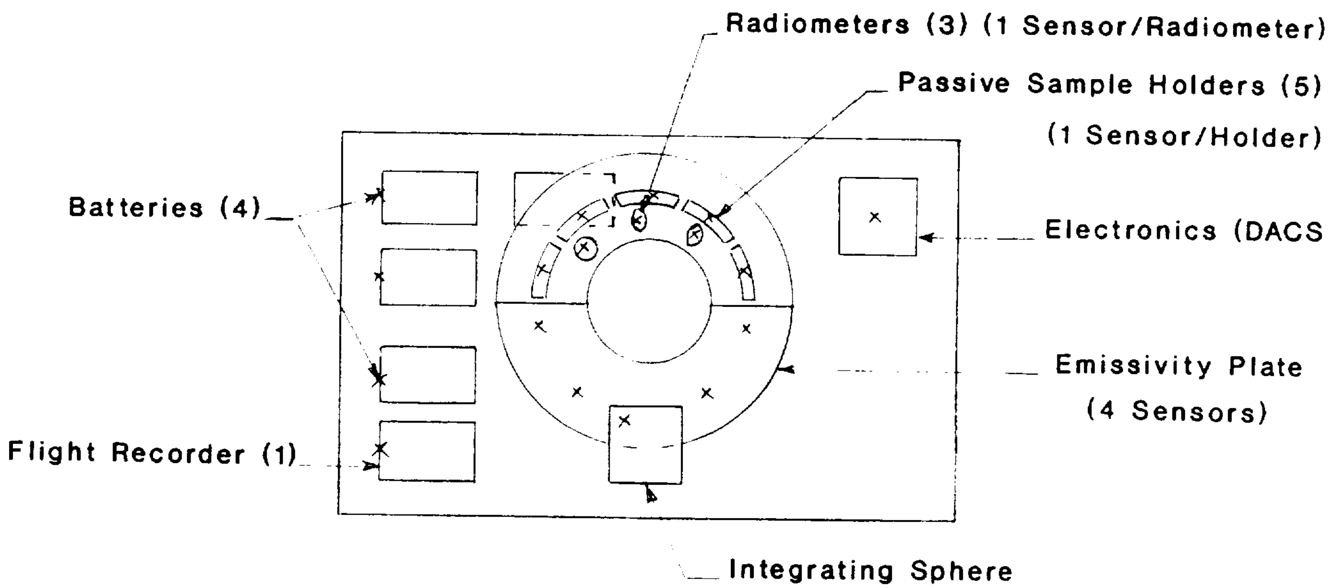
Thermistors were used to sense temperature extremes throughout the TCSE. Fifty three temperature sensors, comprised of thermistors and platinum resistance thermometers (PRT), were installed on the TCSE. The components measured and quantity of

sensors used are given in Figure 31. Only the thermistor data is presented in this report. Figure 32 illustrates the general placement of the thermistors. The DACS recorded the temperature data at predetermined intervals during the TCSE mission until the power source (4 batteries) was expended. Data recovered from the flight recorder were reduced and calibrations applied to determine preliminary temperature data on selected TCSE components. Figure 33 compares predicted data to measured preliminary data for some components, and presents other data for reference. The measured data temperature ranges represent the lowest and highest temperatures recorded by any of the applicable sensors. Figures 34-40 represent typical daily thermal excursions experienced by selected TCSE components.

| Component/Quantity | Type of Sensor | | Quantity of Sensors |
|---|---|---|---|
| | Thermistor | PRT | |
| Integrating Sphere/1 | X | | 1 |
| Batteries/4 | X | | 3 |
| Electronics (DACS)/1 | X | | 2 |
| Emissivity Plate/1 | X | | 4 |
| Radiometers/3 | X | | 3 |
| Passive Sample Holders/5 | X | | 5 |
| Shroud (Top Cover)/1 | X | | 5 |
| Calorimeters/25 | | X | 25 |
| Reference Sensors/4 | X | X | 4 |
| Flight Recorder/1 | X | | 1 |
| | | | 53 |

Figure 31 - Thermal Monitored Components

TCSE Without Cover




X = Sensor Location

TCSE With Cover

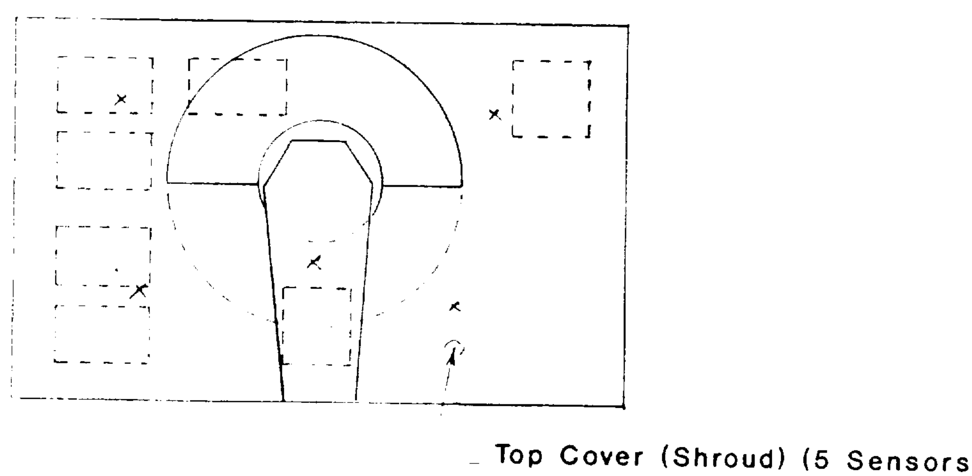



Figure 32 - Thermistor Temperature Sensor Placement

| Component | Predicted Temp. Limit | | Measured Temp. Limit * | |
|---|---|---|---|---|
| | Min (° C) | Max ( °C) | Min (° C) | Max (° C) |
| Integrating Sphere | -25 | 41 | 6 | 19 |
| Batteries | -23 | 43 | 13 | 27 |
| Electronics (DACS) | -27 | 41 | 17 | 29 |
| Emissivity Plate | -25 | 40 | -2 | 17 |
| Radiometers | | | 14 | 39 |
| Passive Sample Hldrs. | | | 15 | 43 |
| Shroud (Front Cover) | | | -43 | 5 |

* Preliminary Data

Figure 33 - Predicted vs. Measured Thermal Data

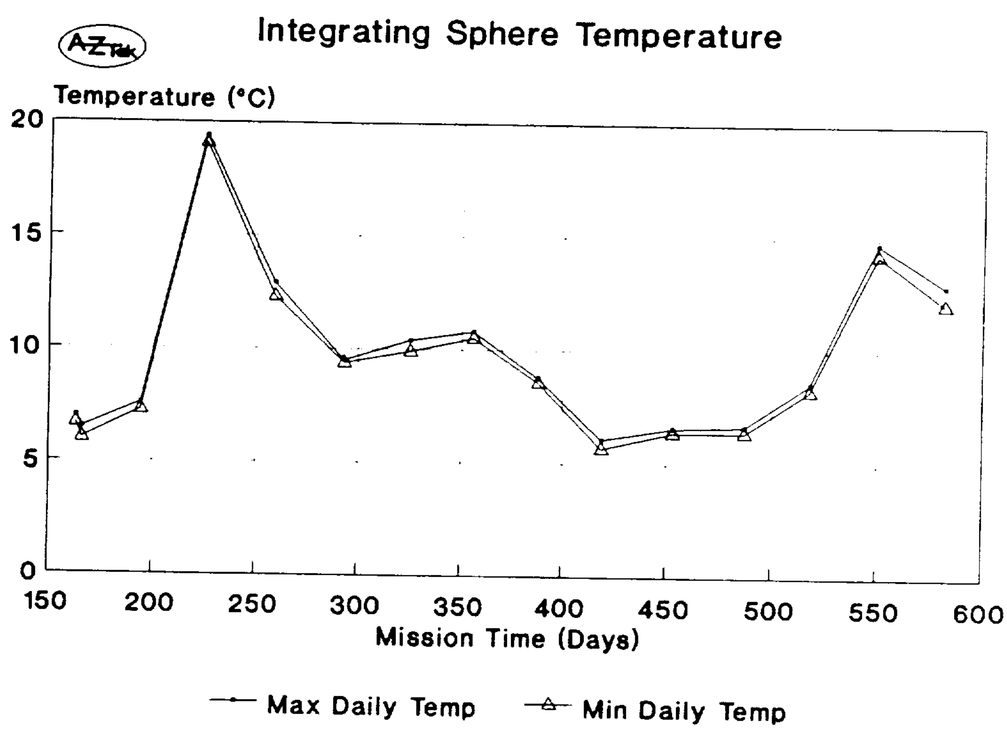



Figure 34 - Integrating Sphere Temperatures

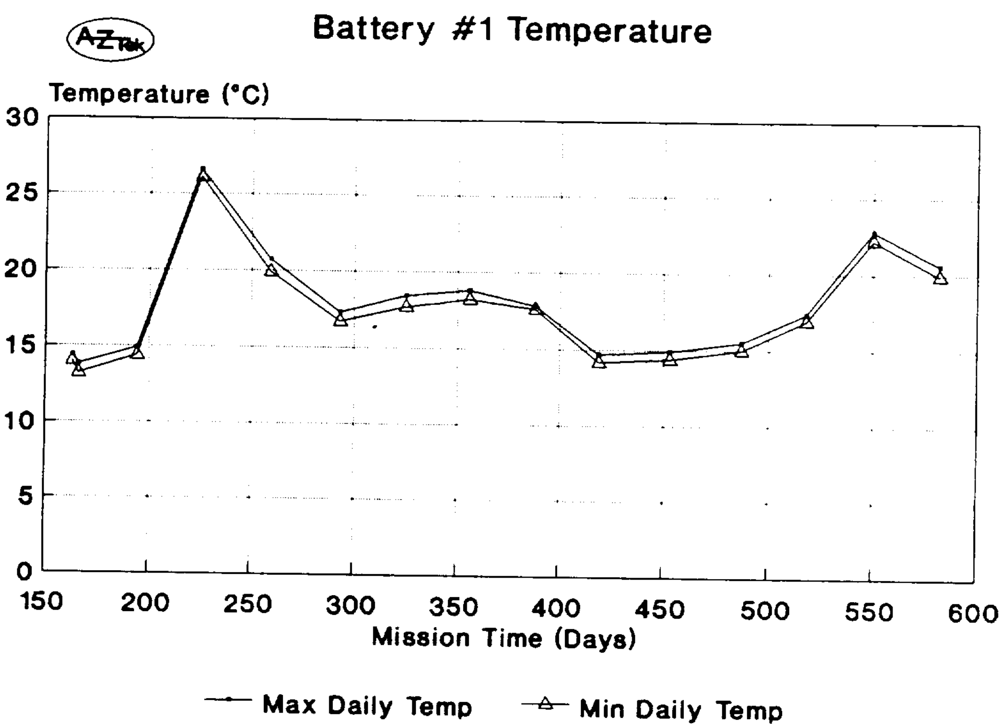



Figure 35 - Battery Temperatures

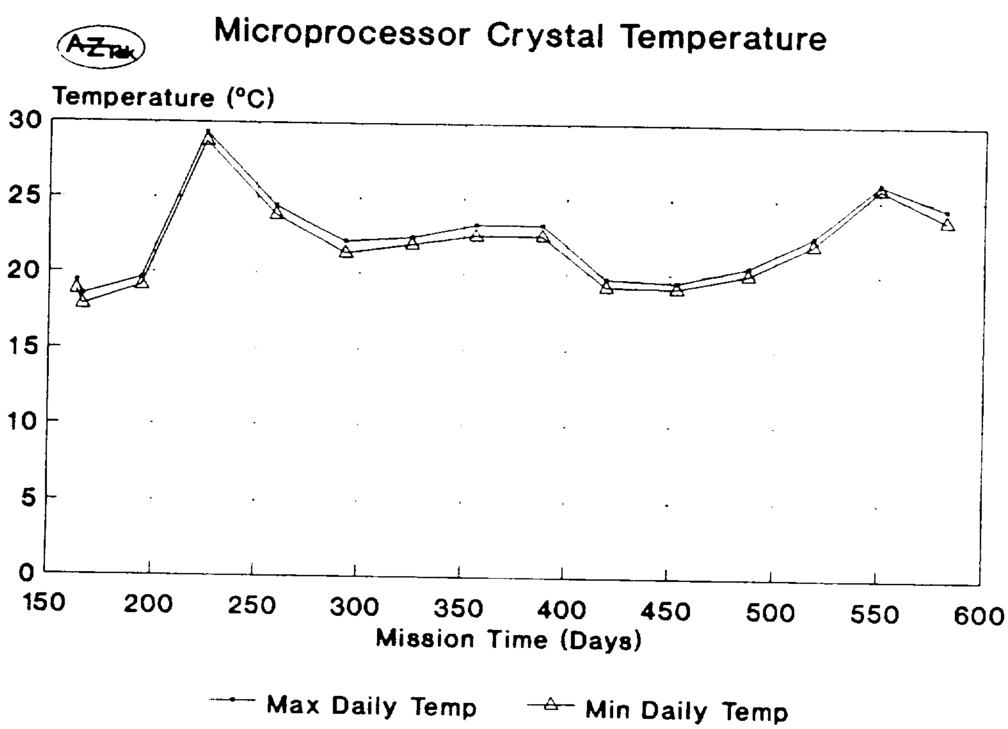



Figure 36 - Microprocessor Crystal Temperatures

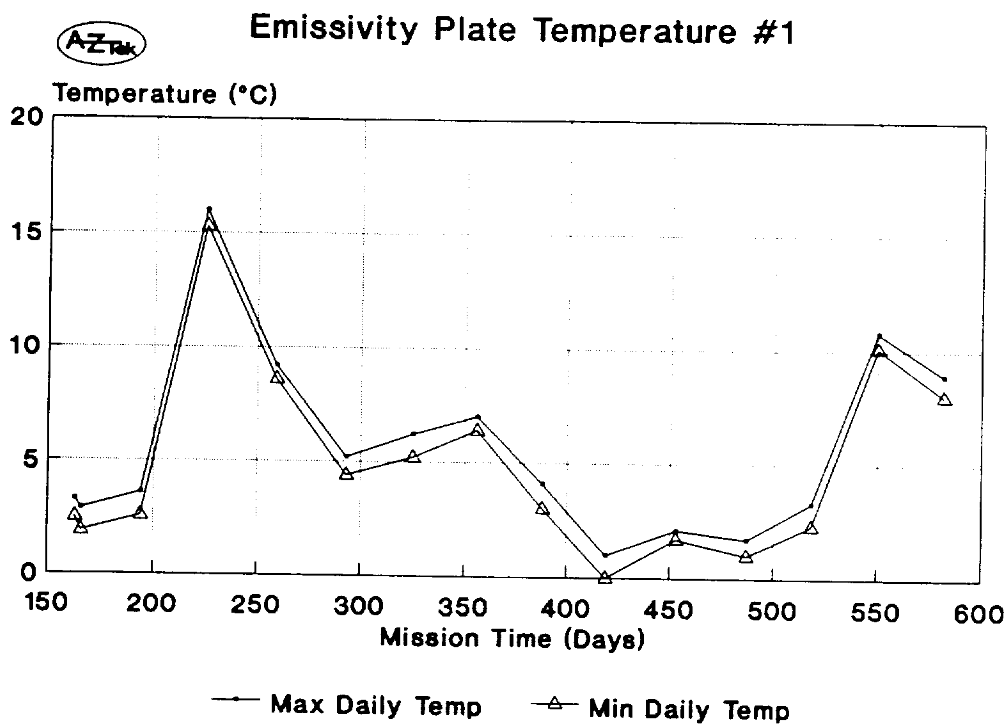



Figure 37 - Emissivity Plate Temperatures

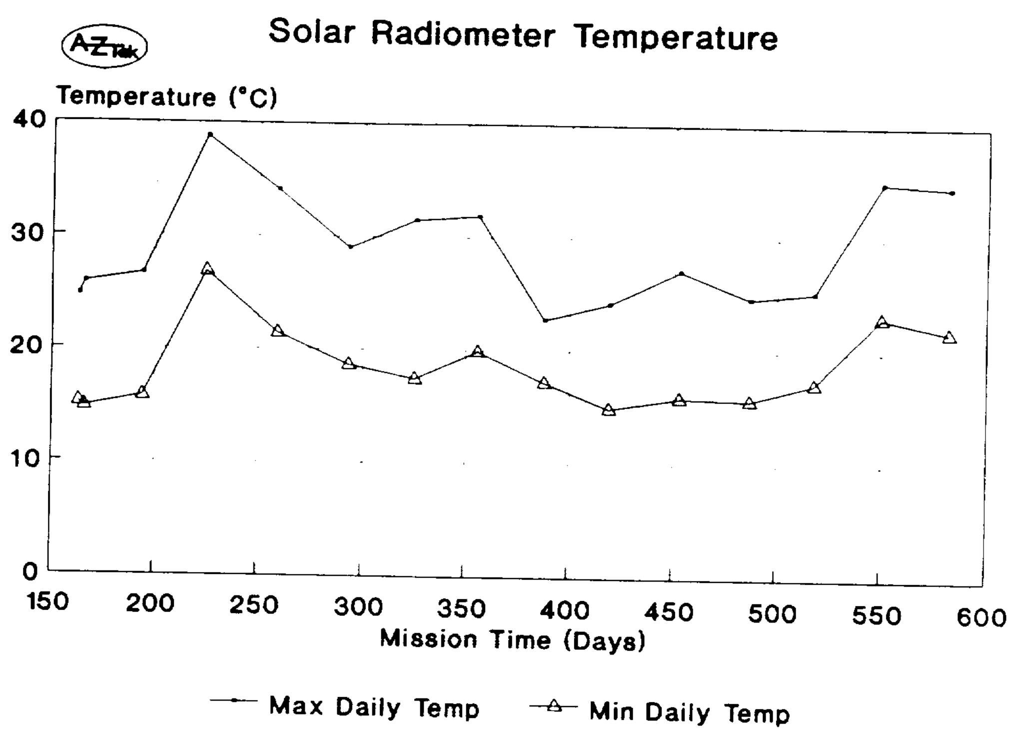



Figure 38 - Solar Radiometer Temperatures

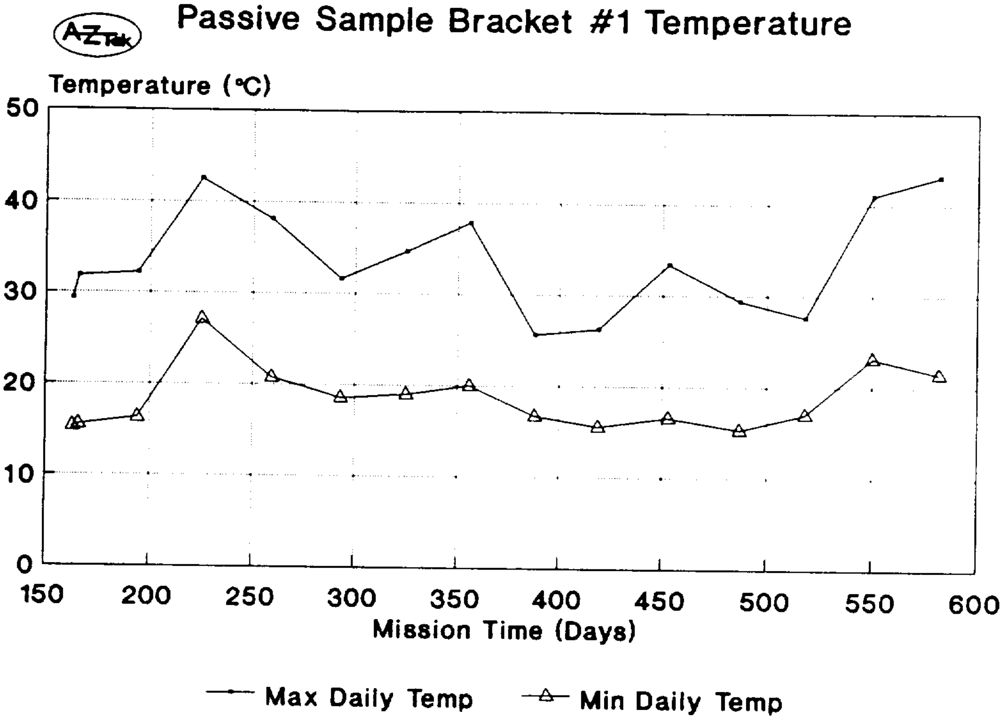



Figure 39 - Passive Sample Holder Temperatures

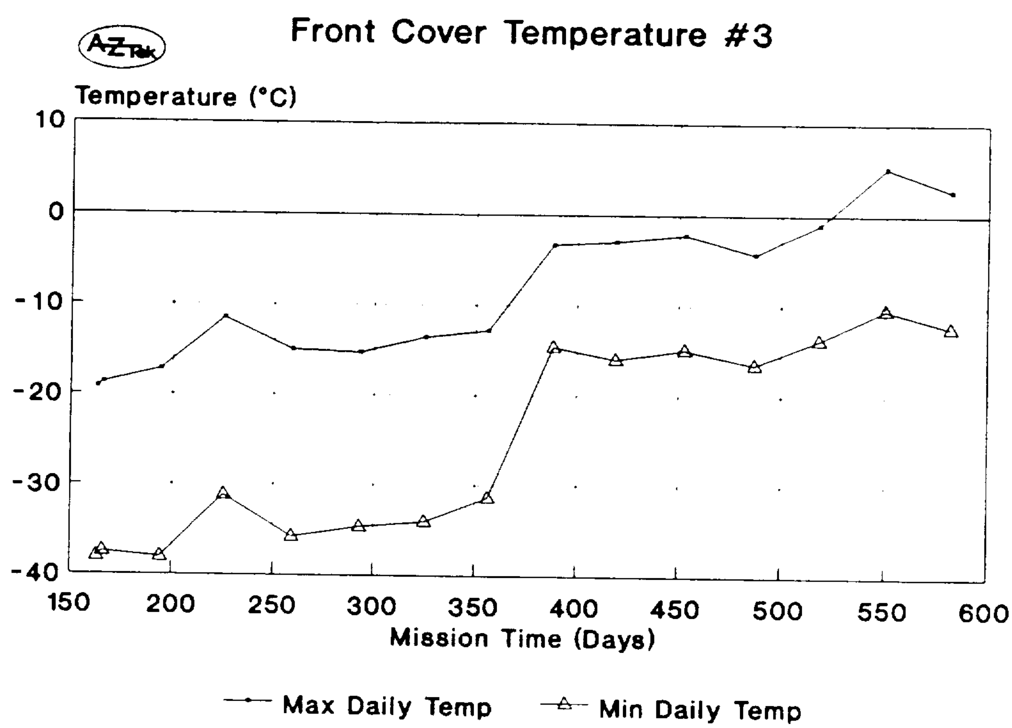



Figure 40 - Front Cover Temperatures

In October, 1990, the LDEF office of NASA Langley Research Center released a post-flight thermal analysis report.[7] Contained in this report are data from their Thermal Measurement System (THERM) Experiment (P0003). This experiment measured solar flux, LDEF structure internal temperatures, and external heat fluxes impinging on LDEF. A cursory check of temperature to compare the THERM experiment to the TCSE has been performed. Of interest is the reported temperature of a radiometer suspended at the center of the LDEF center ring. Data from the P0003 radiometer, representing the LDEF interior structure temperatures, for days 163 through 390 reveals the average temperature of LDEF was approximately $21^{o}$ C. By comparison, the average temperature for the microprocessor crystal, thermally attached to the TCSE and therefore the LDEF structure, was approximately $23^{o}C$. Future analysis will determine the correlation between TCSE to LDEF temperature fluctuations and the known orbital and seasonal parameters.

## 5.0 FLIGHT SAMPLE ANALYSIS

The primary objective of the TCSE mission was to determine the effects of the space environment on thermal control surfaces. The effects and the mechanisms of these changes are very complex because of the synergism of the constituents of the space environment. This effort begins the analysis phase of the TCSE flight samples. Considerable additional analyses will be required to fully understand the effects of the LDEF environment on the TCSE materials and the implications of the results on materials and space vehicle design. This section describes the results of the analyses performed on the TCSE flight samples. Section 5.1 describes the optical measurements that were performed on the test samples while section 5.2 discusses the results of this analysis effort. While some preliminary conclusions can be drawn from these initial analyses, many others will require a more comprehensive analysis effort.

### 5.1 Optical Measurement Description

The primary measurements used for this analysis were total hemispherical reflectance from 250 to 2500 nm. Both in-space and laboratory reflectance measurements were performed on the test samples. Section 2.4.2 described the flight reflectometer which is very similar to the laboratory instrument used for this effort.

Laboratory measurements of spectral reflectance were obtained using a computer controlled Beckman model DK-2A Spectrophotometer equipped with a Gier-Dunkle 203 mm (8 inch) integrat-

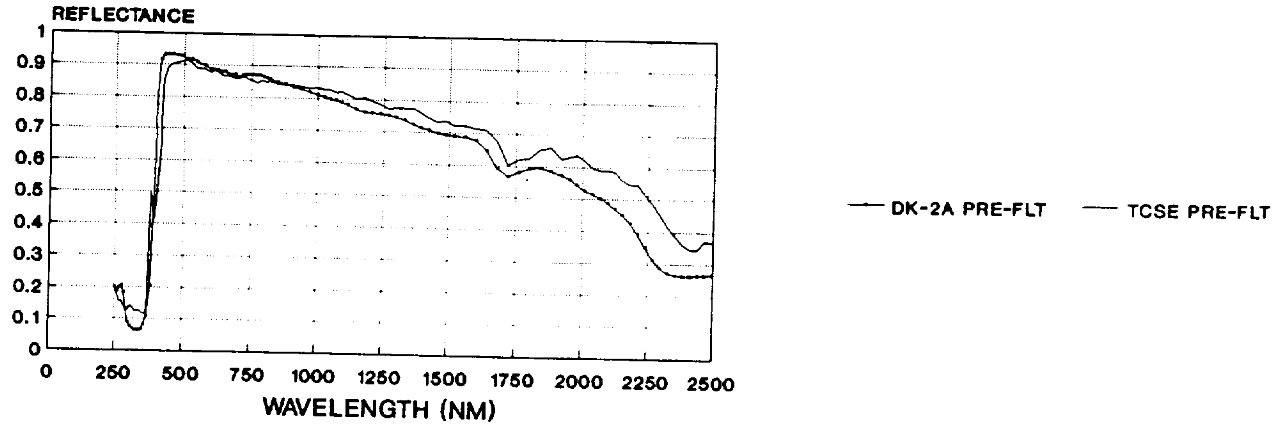
ing sphere. The integrating sphere was coated internally with magnesium oxide ($MgO$ smoke, electrostatically deposited) to provide a near-perfect standard of reflectance. Reflectance data were integrated with respect to the solar spectrum to calculate solar absorptance.[13]

The spectral measurements made with the TCSE reflectometer show differences from the laboratory DK-2A instrument. This is caused by a combination of differing sphere geometries, detector types, and sphere coatings. To enhance the comparison analysis of flight and ground data, a method was developed to correlate the flight data to the laboratory data. The pre-flight DK-2A measurements were compared to the pre-flight measurements made on the TCSE reflectometer and a correlation curve developed for each sample.[14] This correlation curve was applied to each flight measurement to complete the correction. This data correction process is shown in Figure 41.

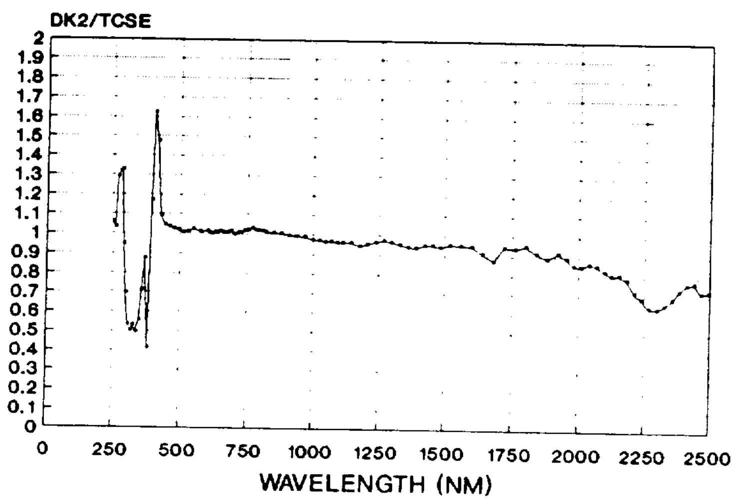
The correlation curve for each sample was developed by a point-by-point division of the DK-2A pre-flight data curve by the pre-flight reflectance measurements made on the TCSE flight instrument. Figure 42 is a typical correlation curve for a high reflectance surface (i.e., white paint). The larger correction values around 350 nm may be due to small wavelength errors in the TCSE monochromator. A small shift at these wavelengths would cause a larger correction because of the fundamental absorption edge of the white paint samples.

The corrections for black samples are more significant. Figure 43 is a typical correlation curve for black samples. At

Step 1. Compare DK-2A and TCSE data




Step 2. Establish Correlation Factor




Factor = DK-2A/TCSE

Step 3. Apply correlation factors to obtain TCSE baseline data

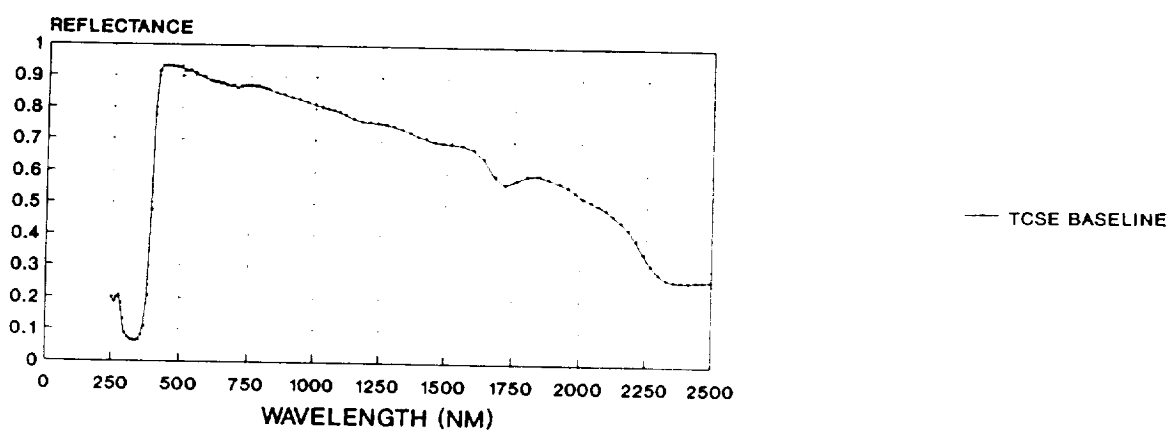
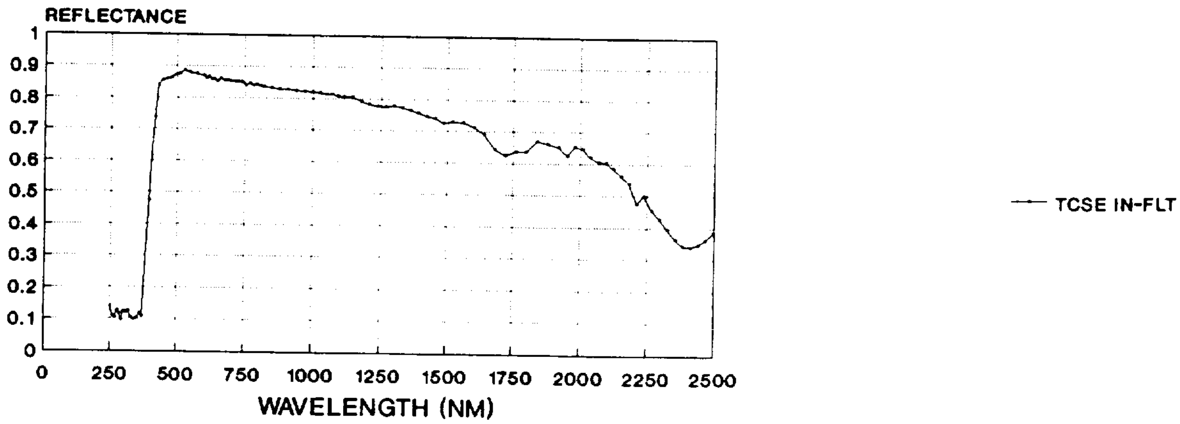
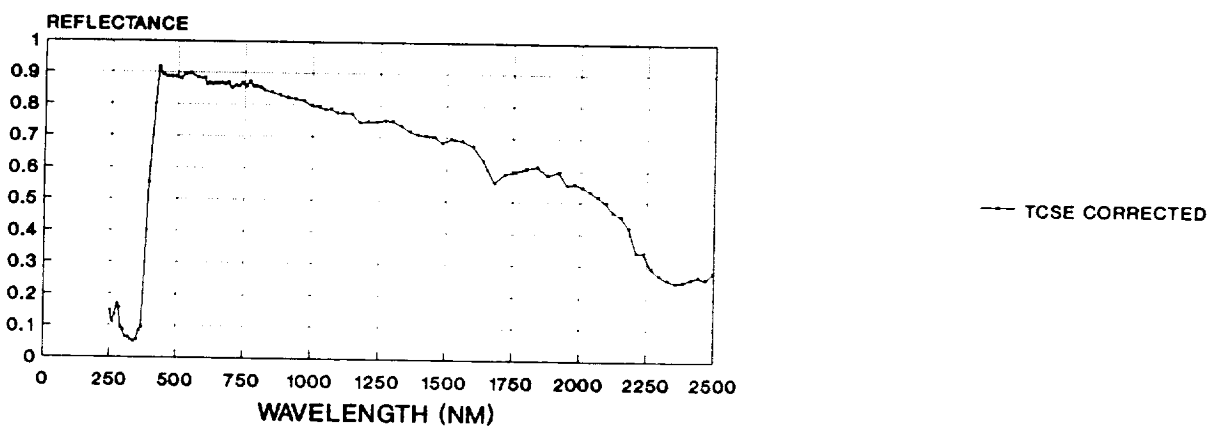



Figure 41 - Flight Data Correlation Process

Step 4. Obtain TCSE in-flight measurements




Step 5. Apply correlation factors (step 2) to in-flight data




Step 6. Now, the TCSE corrected data can be directly compared to the DK-2A post-flight measurement data to determine the magnitude of change in the material properties.

Figure 41 - Flight Data Correlation Process (Continued)

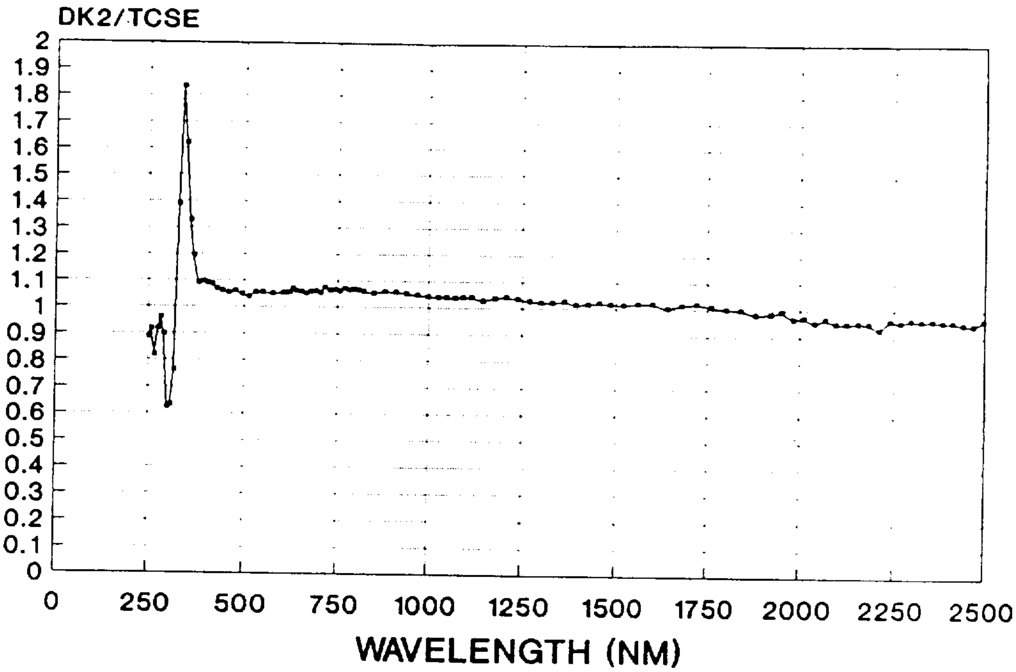



Figure 42 - Typical Correction Curve - YB71/Z93 White Paint

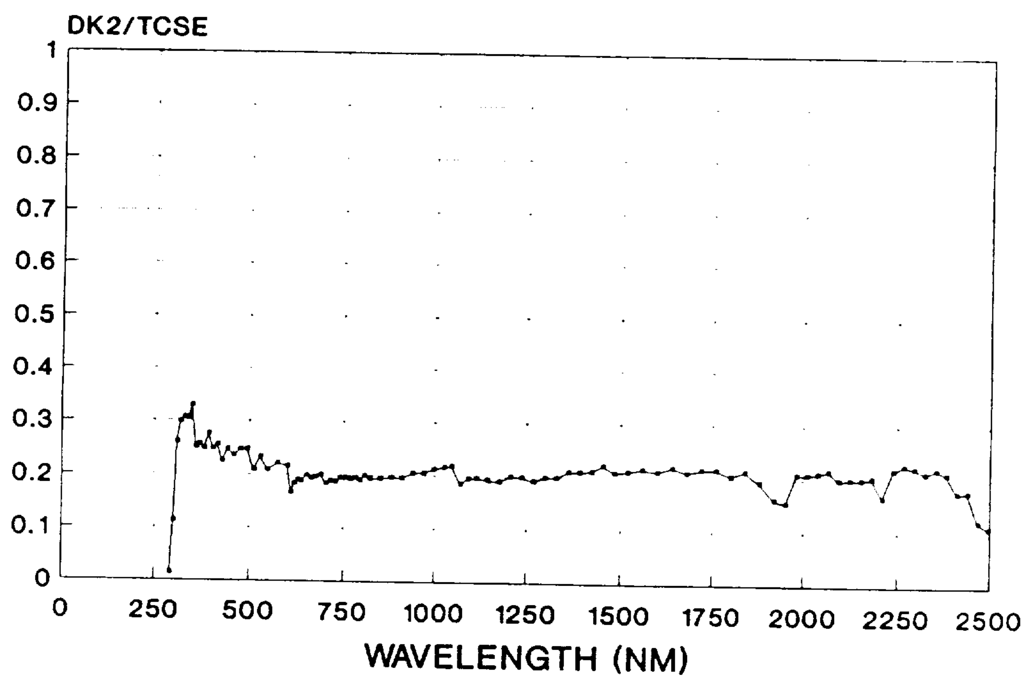



Figure 43-Typical Correction Curve-Z302 Black Paint

this time, it is unknown why the flight instrument reflectance data values for black samples were so high requiring significant corrections to correlate with the laboratory measurement. Once these corrections are applied, the flight measurements compare well to the laboratory measurements.

In addition to the reflectance measurements, the normal emittance of the TCSE samples was also measured using a Gier-Dunkle model DB100 infrared reflectometer.

## 5.2 Analysis Results

Many different changes were observed in the TCSE samples due to their prolonged space exposure. These changes ranged from the obvious cracking and peeling of the overcoated samples to the subtile changes of UV fluorescence in some samples. Some samples changed more than expected while others changed less than expected.

The measured effects of the atmospheric atomic oxygen are probably the most significant because of the large total AO fluence ($8 \times 10^{21}$ atoms/cm$^2$)[6] on the TCSE surfaces due to the LDEF orbital attitude.

Figures 44 and 45 are pre-flight and post-flight photographs of the TCSE samples showing changes to many of the samples. Figure 46 shows the position and material of each of the 49 TCSE flight samples. Figures 47 - 50 summarize the optical measurements on the TCSE flight samples.

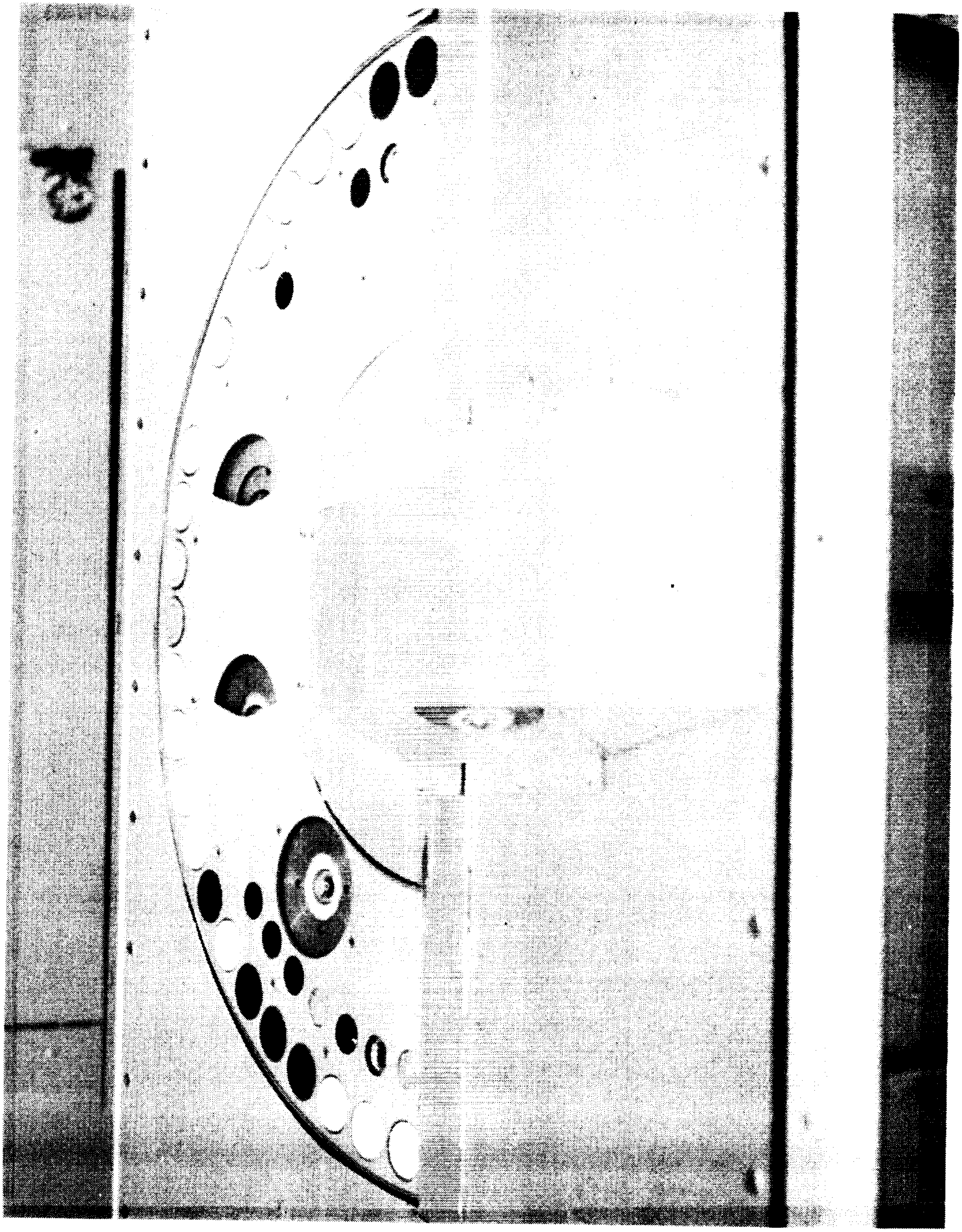


Figure 44 - Pre-flight Photograph of the TCSE Flight Samples

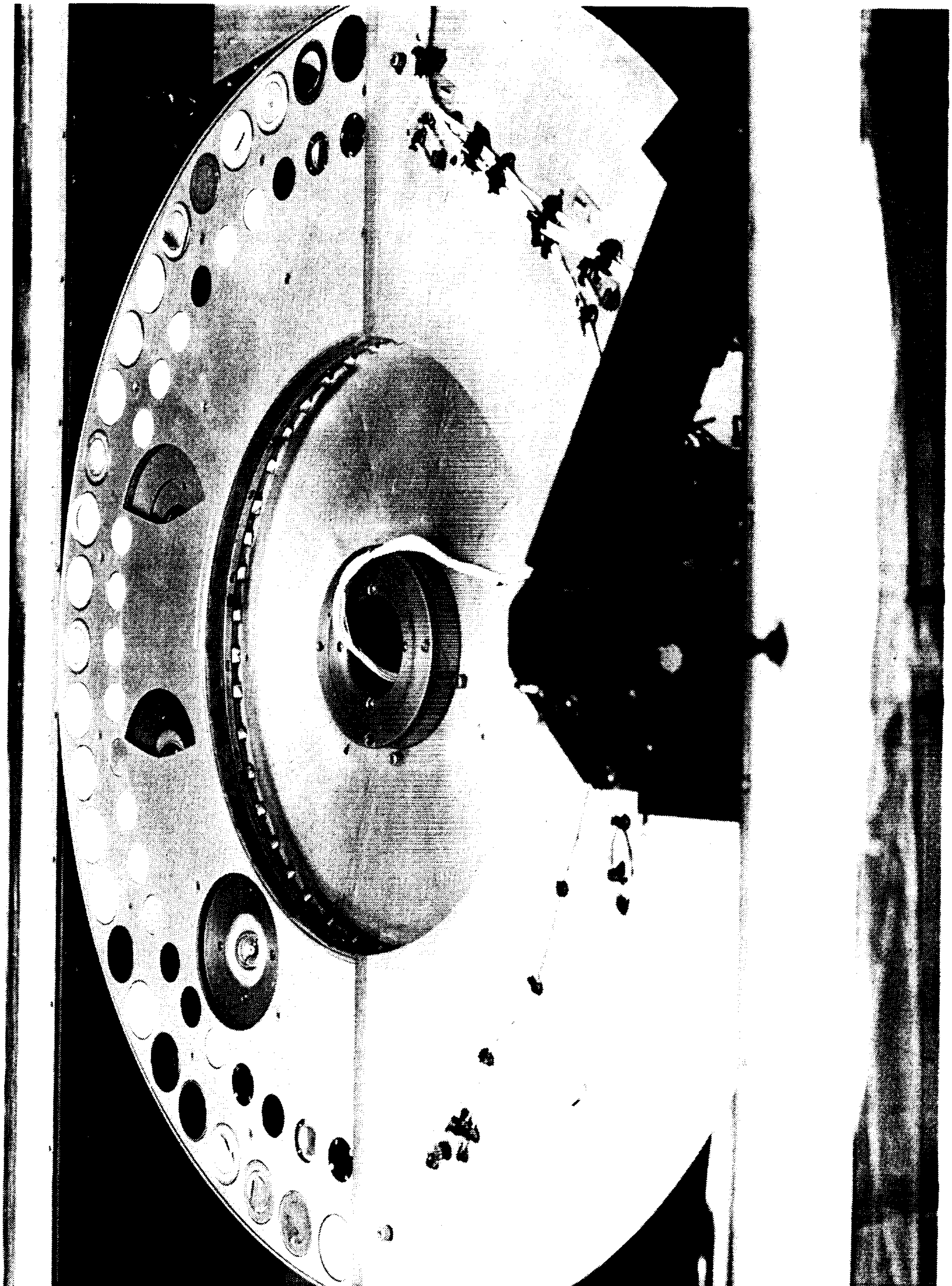
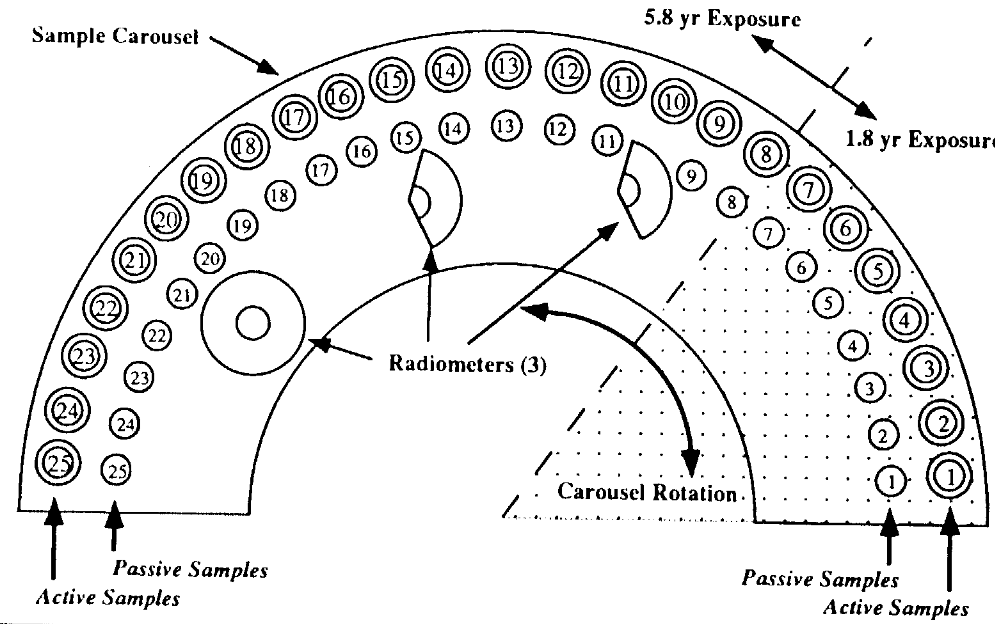


Figure 45 - Post-flight Photograph of the TCSE Flight Samples




| TCSE Active Samples | | |
|---|---|---|
| ***Sample #*** | ***Material*** | ***C ID #*** |
| 13 | Ag/Teflon | C 90 |
| 14 | YB 71/Z 93 | C 93 |
| 15 | S13G/LO | C 92 |
| 16 | YB 71 | C 96 |
| 17 | Z 93 | C 95 |
| 18 | D-111 | C 99 |
| 19 | Tedlar | C110 |
| 20 | Z 302/RTV 670 | C105 |
| 21 | Z 302/OI 650 | C104 |
| 22 | Z 302 | C101 |
| 23 | A 276/RTV 670 | C 88 |
| 24 | A 276/OI 650 | C 87 |
| 25 | A 276 | C 82 |

| TCSE Passive Samples | | |
|---|---|---|
| ***Sample #*** | ***Material*** | ***P ID #*** |
| 13 | YB 71 | P 2 |
| 14 | Tedlar | P23 |
| 15 | A 276/OI 650 | P13 |
| 16 | A 276 | P11 |
| 17 | Tedlar | P24 |
| 18 | A 276/RTV 670 | P16 |
| 19 | Z 302/RTV 670 | P21 |
| 20 | Z 302/OI 650 | P20 |
| 21 | Z 302 | P17 |
| 22 | Silver | ••• |
| 23 | Z 302/OI 650 | P22 |
| 24 | KRS-5 | ••• |
| 25 | Silver | ••• |

| TCSE Passive Samples | | |
|---|---|---|
| ***Sample #*** | ***Material*** | ***P ID #*** |
| 1 | Silver | ••• |
| 2 | KRS-5 | ••• |
| 3 | Z 302 | P18 |
| 4 | Z 93 | P 5 |
| 5 | YB 71/Z 93 | P 4 |
| 6 | D-111 | P10 |
| 7 | YB 71 | P 1 |
| 8 | A 276 | P12 |
| 9 | Z 93 | P 6 |
| 10 | • No Sample • | ••• |
| 11 | YB 71/Z 93 | P 3 |
| 12 | S13G/LO | P7 |

| TCSE Active Samples | | |
|---|---|---|
| ***Sample #*** | ***Material*** | ***C ID #*** |
| 1 | Z 302 | C102 |
| 2 | Z 302/RTV 670 | C108 |
| 3 | A 276/RTV 670 | C100 |
| 4 | A 276 | C 83 |
| 5 | Anodize | C 63 |
| 6 | Diffuse Ag/Teflon | C 73 |
| 7 | YB 71 White Paint | C 97 |
| 8 | Ag/Teflon | C 75 |
| 9 | YB 71/Z 93 | C 94 |
| 10 | Anodize | C 61 |
| 11 | Diffuse Ag/Teflon | C 74 |
| 12 | Ag/Teflon | C 76 |

Figure 46 - TCSE Sample Identification

Corrected Solar Absorptance vs. Exposure

| Exposure (Months) | | 0 | 6.5 | 7.5 | 8.6 | 9.8 | 11.9 | 12.9 | 14.0 | 15.0 | 16.2 | 69.2 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MATERIAL | SAMPLE # | PRE-FLT | | | | | | | | | | POST FLIGHT | $\Delta\alpha_s$ |
| Z93 | C95 | .140 | .124 | .120 | .125 | .122 | .119 | .120 | .124 | .129 | .125 | .150 | .010 |
| YB71/Z93 | C93 | .101 | .080 | .075 | .080 | .079 | .078 | .080 | .078 | .087 | x | .118 | .017 |
| YB71/Z93 | C94 | .101 | .100 | .098 | .104 | .102 | .106 | .105 | .106 | .114 | x | .112 | .011 |
| YB71 | C96 | .138 | .115 | .115 | .116 | .119 | .115 | x | .116 | .126 | x | .153 | .025 |
| YB71 | C97 | .110 | .092 | .097 | x | .095 | .096 | .096 | .102 | x | x | .131* | .021 |
| A276 | C82 | .253 | .276 | .264 | .287 | .279 | .281 | .300 | .304 | .305 | .330 | .236 | -.017 |
| A276 | C83 | .255 | .261 | .271 | x | x | x | x | x | x | x | .272* | .017 |
| A276/OI650 | C87 | .247 | .436 | .455 | .476 | .506 | .525 | .542 | .544 | .541 | .554 | .592 | .345 |
| A276/RTV670 | C88 | .266 | .464 | .470 | .486 | .500 | .510 | .522 | .525 | .533 | .529 | .623 | .357 |
| A276/RTV670 | C100 | .258 | x | .270 | Coating gone by 8.6 months exposure | | | | | | | | ---- |
| S13G/LO | C92 | .168 | .176 | .176 | .193 | .195 | .203 | x | .216 | .221 | x | .368 | .200 |
| Tedlar | C110 | .248 | .263 | .262 | .260 | .264 | .261 | .259 | .260 | .258 | .260 | .224 | -.024 |
| Anodize | C61 | .409 | .461 | .466 | .465 | .487 | .495 | .502 | .506 | .504 | x | .466 | .057 |

x - Data unavailable
* - 19.5 months exposure

Figure 47 - Active Sample $\alpha_s$ Summary

Corrected Solar Absorptance vs. Exposure

| Exposure (Months) | | 0 | 6.5 | 7.5 | 8.6 | 9.8 | 11.9 | 12.9 | 14.0 | 15.0 | 16.2 | 69.2 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MATERIAL | SAMPLE # | PRE-FLT | | | | | | | | | | POST FLIGHT | $\Delta\alpha_s$ |
| Anodize | C63 | .402 | .456 | .462 | x | .485 | .494 | .497 | .503 | x | x | .540* | .138 |
| Ag-Tef-5 mil | C75 | .063 | x | x | x | x | x | x | x | x | x | .076 | .013 |
| Ag-Tef-5 mil | C76 | .058 | .053 | .049 | .049 | .073 | .058 | .054 | .056 | .059 | x | .075 | .017 |
| Ag-Tef-2 mil | C90 | .075 | .064 | .062 | .063 | .082 | .075 | .075 | .076 | .081 | x | .161 | .086 |
| Ag-Tef-diff | C73 | .077 | x | x | x | x | x | x | x | x | x | .100* | .023 |
| Ag-Tef-diff | C74 | .075 | .067 | .065 | .071 | .074 | .073 | .073 | .077 | .077 | x | .103 | .028 |
| D111 | C99 | .980 | .985 | .985 | .986 | .985 | .986 | .986 | .986 | .986 | x | .996 | .016 |
| Z302 | C101 | .975 | .981 | .982 | .981 | .981 | .980 | .983 | .980 | .979 | .981 | .603 | ** |
| Z302 | C102 | .976 | x | .983 | x | x | x | x | x | x | x | .982* | .006 |
| Z302/OI650 | C104 | .983 | .986 | .986 | .986 | .986 | .986 | .986 | .986 | .986 | .986 | .990 | .007 |
| Z302/RTV670 | C105 | .985 | .987 | .987 | .988 | .987 | .988 | .988 | .987 | .988 | .986 | .988 | .003 |
| Z302/RTV670 | C108 | .984 | x | .984 | x | x | x | x | x | x | x | .983* | -.001 |

x - Data unavailable
* - 19.5 months exposure
** - Coating eroded away leaving primer

Figure 47 - Active Sample $\alpha_s$ Summary (Continued)

| MATERIAL | SAMPLE # | SPACE EXPOSURE (MONTHS) | SOLAR ABSORPTANCE ( $\alpha_S$ ) PRE-FLIGHT | POST-FLIGHT | $\Delta\alpha_S$ |
|---|---|---|---|---|---|
| D111 | P10 | 19.5 | .992 | .992 | 0 |
| Z302 | P17 | 69.2 | .970 | .570 | * |
| Z302 | P18 | 19.5 | .969 | .994 | .025 |
| Z302/OI650 | P20 | 69.2 | .983 | .985 | .002 |
| Z302/OI650 | P22 | 69.2 | .982 | .978 | - .004 |
| Z302/RTV670 | P21 | 69.2 | .980 | .979 | - .001 |
| Z93 | P5 | 19.5 | .142 | .151 | .009 |
| Z93 | P6 | 69.2 | .133 | .134 | .001 |
| YB71 | P1 | 19.5 | .143 | .150 | .007 |
| YB71/Z93 | P3 | 69.2 | .084 | .089 | .005 |
| YB71/Z93 | P4 | 19.5 | .089 | .085 | - .005 |
| YB71 | P2 | 69.2 | .152 | .181 | .029 |
| A276 | P11 | 69.2 | .262 | .268 | .006 |
| A276 | P12 | 69.2 | .257 | .230 | - .027 |
| A276/OI650 | P13 | 69.2 | .256 | .583 | .327 |
| A276/RTV670 | P16 | 69.2 | .282 | .524 | .242 |
| S13G/LO | P7 | 69.2 | .200 | .418 | .218 |
| Tedlar | P23 | 69.2 | .253 | .214 | - .039 |
| Tedlar | P24 | 69.2 | .241 | .213 | - .028 |

* Coating eroded away leaving primer

Figure 48 - Passive Sample $\alpha_S$ Summary

Emittance Measurements

| Sample # | Material | Sample ID# | Control | Postflight |
|---|---|---|---|---|
| 1 | Z302 Black Paint | C102 | .912 | .920 |
| 2 | Z302/RTV670 | C108 | .907 | * |
| 3 | A276/RTV670 | C100 | .907 | * |
| 4 | A276 White Paint | C83 | .897 | * |
| 5 | Anodize | C63 | .840 | .839 |
| 6 | Diffuse Silver Teflon | C73 | .821 | .817 |
| 7 | YB71 White Paint | C97 | .901 | .880 |
| 8 | Silver Teflon | C75 | .812 | .802 |
| 9 | YB71 over Z93 | C94 | .849 | .878 |
| 10 | Anodize | C61 | .840 | .834 |
| 11 | Diffuse Silver Teflon | C74 | .917 | .788 |
| 12 | Silver Teflon | C76 | .812 | .782 |
| 13 | Silver Teflon | C90 | .812 | .458 |
| 14 | YB71 over Z93 | C93 | .849 | .880 |
| 15 | S13G/LO White Paint | C92 | .900 | .883 |
| 16 | YB71 White Paint | C96 | .901 | .880 |
| 17 | Z93 White Paint | C95 | .915 | .918 |
| 18 | IITRI D111 Black Paint | C99 | .929 | .903 |
| 19 | Tedlar White Film | C110 | .899 | .936 |
| 20 | Z302/RTV670 | C105 | .907 | .899 |
| 21 | Z302/OI650 | C104 | .905 | .896 |
| 22 | Z302 Black Paint | C101 | .912 | * |
| 23 | A276/RTV670 | C88 | .907 | * |
| 24 | A276/OI650 | C87 | .896 | * |
| 25 | A276 White Paint | C82 | .897 | .931 |

* - Unable to measure due to sample condition

Figure 49 - Active Sample $\varepsilon_T$ Summary

Emittance Measurements

| Sample # | Material | Sample ID# | Control | Postflight |
|---|---|---|---|---|
| 1 | Auger Silver Sample | ---- | ---- | .461 |
| 2 | KRS-5 IR Crystal | ---- | ---- | ---- |
| 3 | Z302 Black Paint | P18 | .912 | .928 |
| 4 | Z93 White Paint | P5 | .915 | .930 |
| 5 | YB71 over Z93 | P4 | .849 | .857 |
| 6 | IITRI D111 Black Paint | P10 | .929 | .921 |
| 7 | YB71 | P1 | .849 | .901 |
| 8 | A276 White Paint | P12 | .897 | .931 |
| 9 | Z93 White Paint | P6 | .915 | .921 |
| 10 | No Sample | ---- | ---- | ---- |
| 11 | YB71 over Z93 | P3 | .849 | .863 |
| 12 | S13G/LO White Paint | P7 | .900 | .887 |
| 13 | YB71 White Paint | P2 | .901 | .905 |
| 14 | Tedlar White Film | P23 | .899 | .939 |
| 15 | A276/OI650 | P13 | .896 | .893 |
| 16 | A276 White Paint | P11 | .897 | .920 |
| 17 | Tedlar White Film | P24 | ---- | .925 |
| 18 | A276/RTV670 | P16 | .907 | .877 |
| 19 | Z302/RTV670 | P21 | .907 | .889 |
| 20 | Z302/OI650 | P20 | .905 | .894 |
| 21 | Z302 Black Paint | P17 | .912 | .901 |
| 22 | Auger Silver Sample | ---- | ---- | .307 |
| 23 | Z302/OI650 | P22 | .905 | .892 |
| 24 | KRS-5 IR Crystal | ---- | ---- | ---- |
| 25 | Auger Silver Sample | ---- | ---- | .532 |

---- Not Applicable

Figure 50 - Passive Sample $\varepsilon_T$ Summary

Additional microscopic analysis was performed on the TCSE samples.[14] The analysis concentrated on surface features and micrometeoroid debris impact effects.

The following sections first discuss the different sample materials followed by a discussion of the overall results.

### 5.2.1 A276 White Paint

Chemglaze A276 polyurethane white paint has been used on many short term space missions including Spacelab. It was known to degrade moderately under long term UV exposure and to be susceptible to AO erosion [1,15]. To evaluate the effectiveness of AO protective coatings, A276 samples were flown with and without overcoatings. Two materials were used as protective coatings over A276--RTV670 and Owens Illinois OI650.

The post-flight condition of the A276 samples were somewhat surprising in that the unprotected TCSE A276 samples are very white. Previous flight and laboratory tests indicate that almost six years of solar UV exposure should have rendered the A276 a medium brown color. The overcoated TCSE samples, however, do exhibit the characteristic UV darkening. Initial visual inspection at KSC of unprotected A276 samples on the trailing edge of LDEF (almost no AO exposure) showed that they also degraded as expected.

Apparently, as the unprotected A276 samples on the RAM side of LDEF degraded, their surfaces were eroded away leaving a fresh, undamaged surface. Pippin[16] reported that the A276 binder eroded away leaving the white pigment exposed. Some

degradation of this $TiO_2$ pigment should have also been observed due to UV exposure (in the absence of AO). It is possible that there was sufficient oxygen on leading edge surfaces to inhibit oxygen based pigment damage.[17]

Figure 51 shows pre-flight, in-space, and post-flight measurement of solar absorptance ( $\alpha_s$ ) for the unprotected A276 and overcoated A276 samples. Figures 52-54 are the detailed reflectance curves for selected A276 samples. These data show that both protective coatings protected the A276 from AO erosion but allowed the A276 coating to degrade from solar UV exposure. Some degradation may be due to darkening of the thin overcoating. This will be investigated in future analyses.

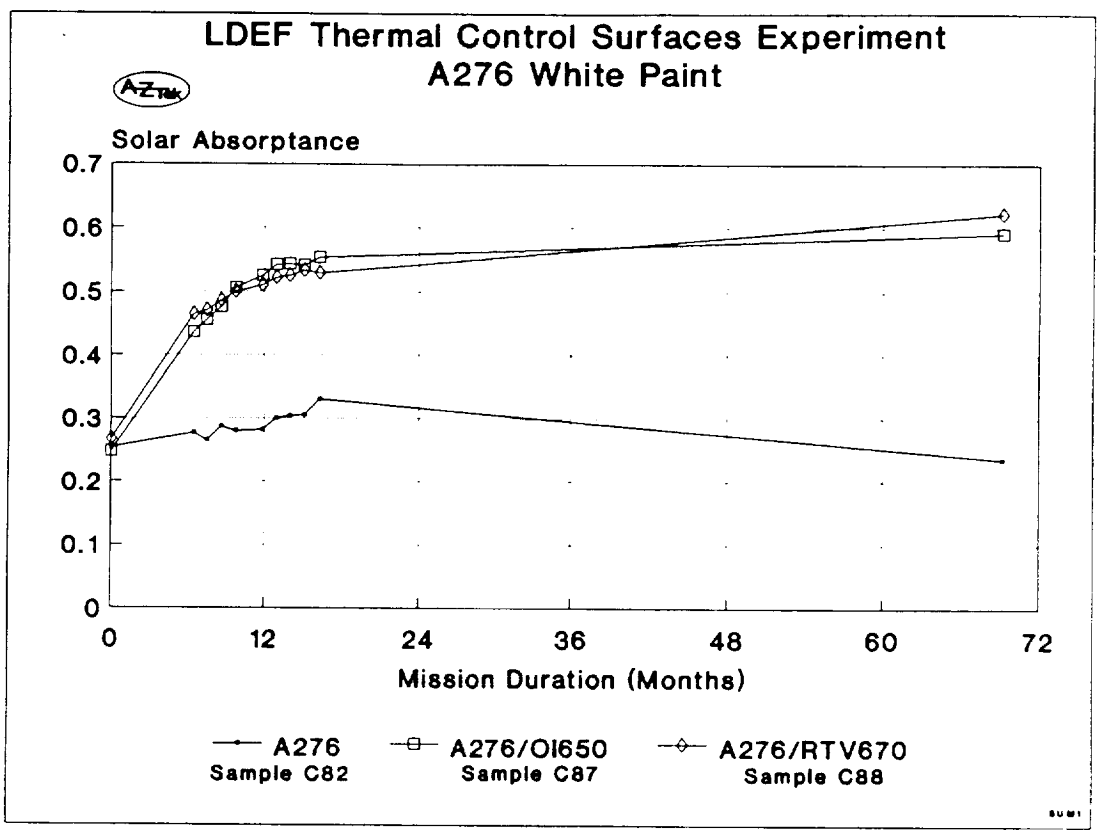



Figure 51 - Flight Performance of A276

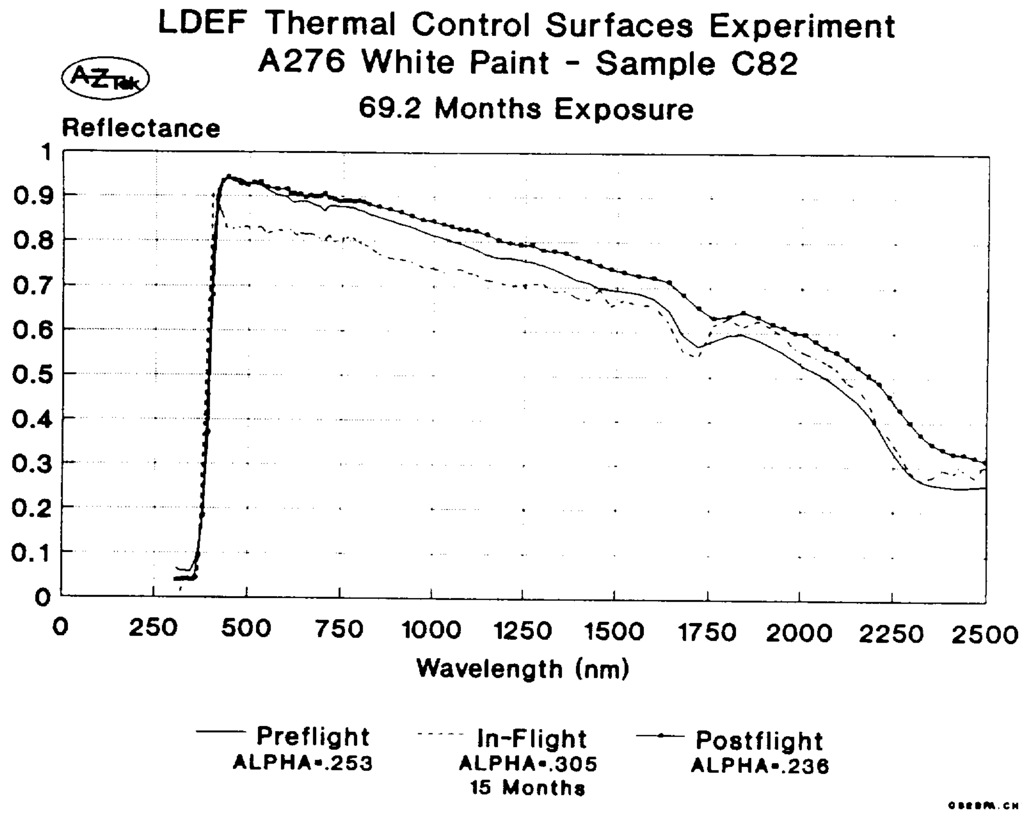



Figure 52 - Reflectance of A276 Flight Sample

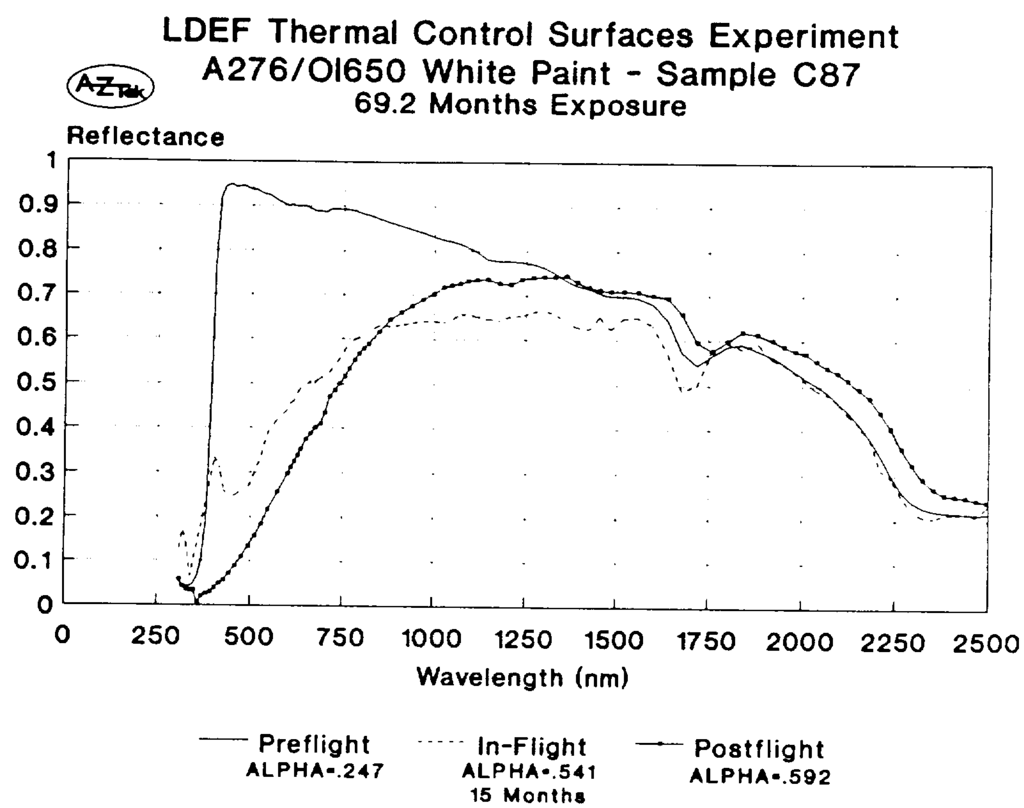



Figure 53 - Reflectance of OI650 over A276 Flight Sample

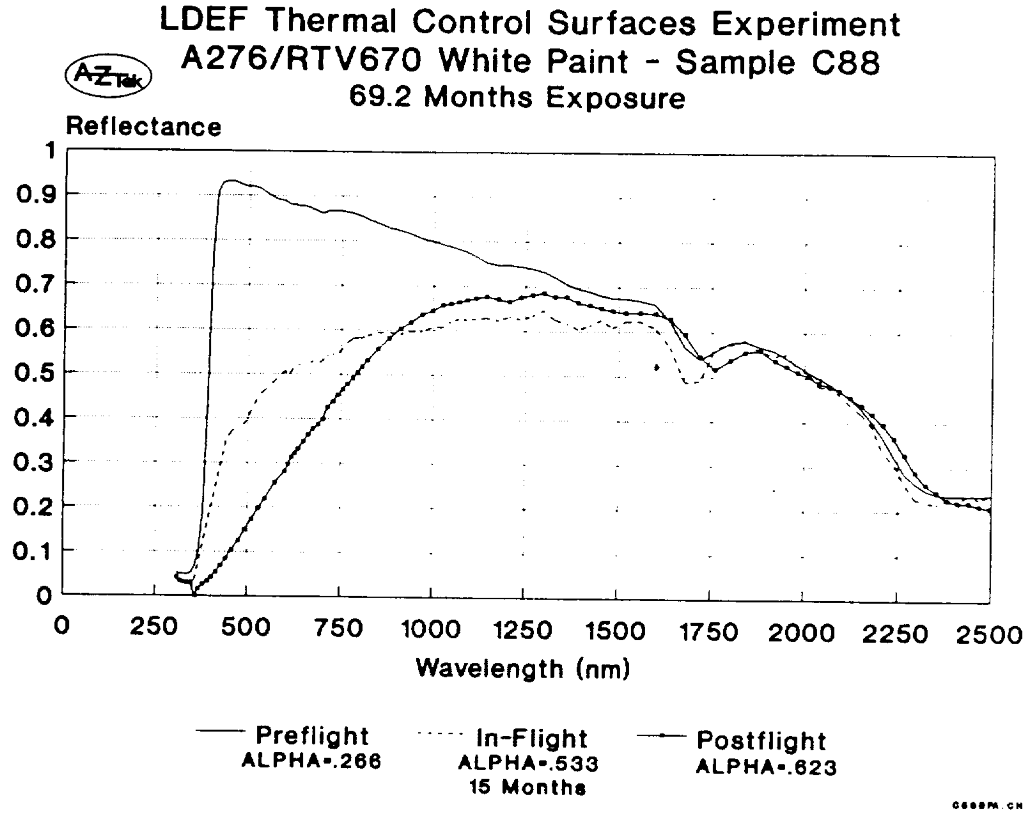



Figure 54 - Reflectance of RTV670 over A276 Flight Sample

The data for the unprotected A276 shows only a small amount of degradation early in the almost 6 year exposure. While most of the AO fluence occurred late in the LDEF mission, the TCSE in-space measurements show there was sufficient AO present early in the mission to inhibit UV degradation.

Figures 55 and 56 show physical damage on the overcoated A276 calorimeter samples. The unprotected A276 samples (see Figure 57) did not crack or peel. The passive samples with these same protective coatings also crazed and cracked but did not peel. The calorimeter samples were thermally isolated from the TCSE structure and therefore saw wider temperature excursions, possibly causing the peeling of the overcoated samples.

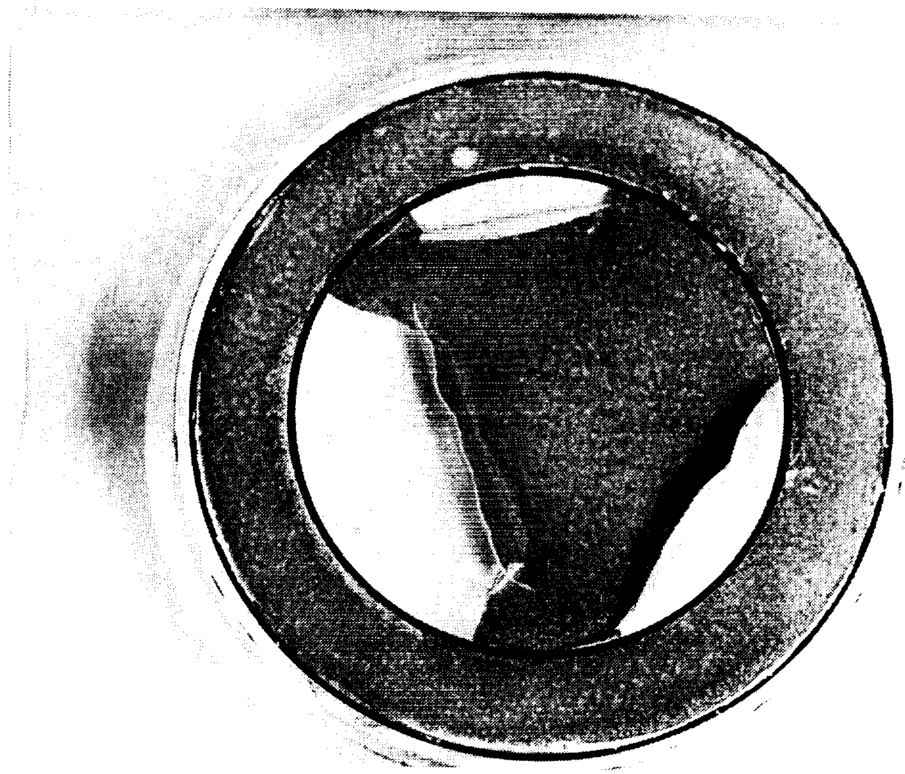


Figure 55 - Post-flight Photograph of RTV670 over A276 Flight Sample C88

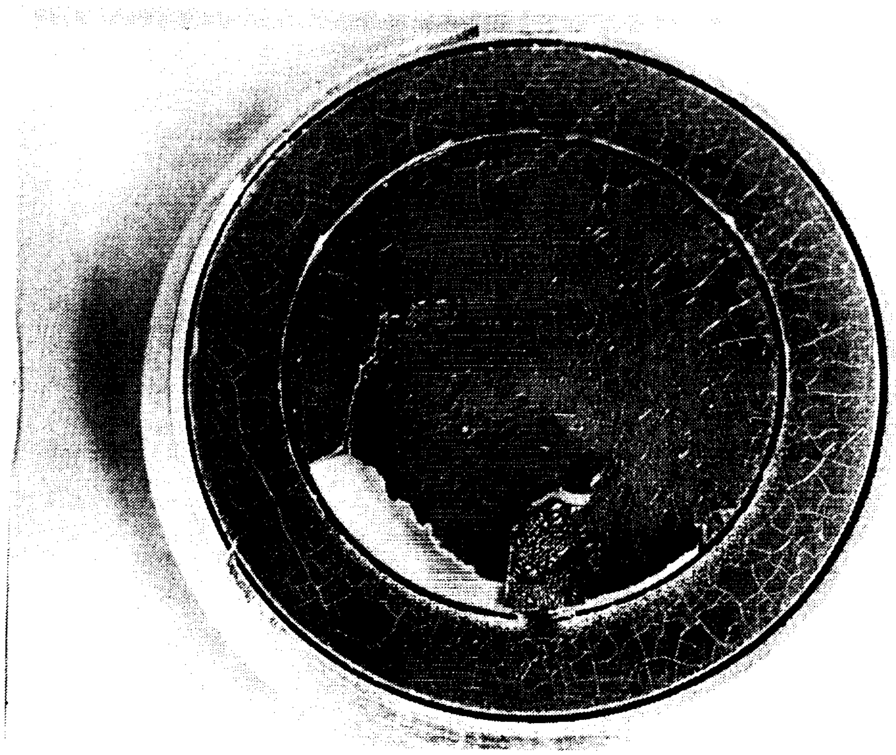


Figure 56 - Post-flight Photograph of OI650 over A276 Flight Sample C87

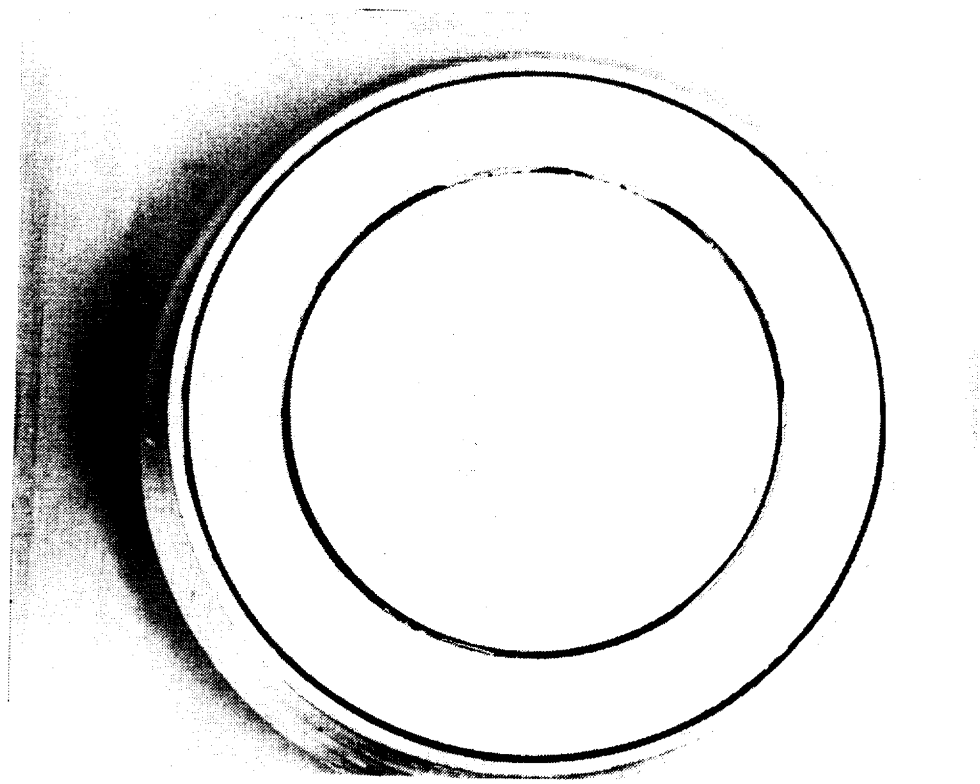


Figure 57 - Post-flight Photograph of A276 Flight Sample C82

The extended space exposure also changed the UV fluorescence of both the A276 and overcoated A276 coatings. This fluorescence is easily seen using a short wavelength inspection black light. The RTV670 and OI650 coatings glow a bright yellow under this UV illumination. Preliminary measurements show both a change in the peak wavelength and an increase in the magnitude of the fluorescence.

5.2.2 <u>Z93 White Paint</u>

The Z93 white thermal control coatings flown on the TCSE were almost impervious to the 69 month LDEF mission (see Figures 58 and 59). The Z93 samples showed an initial improvement in the

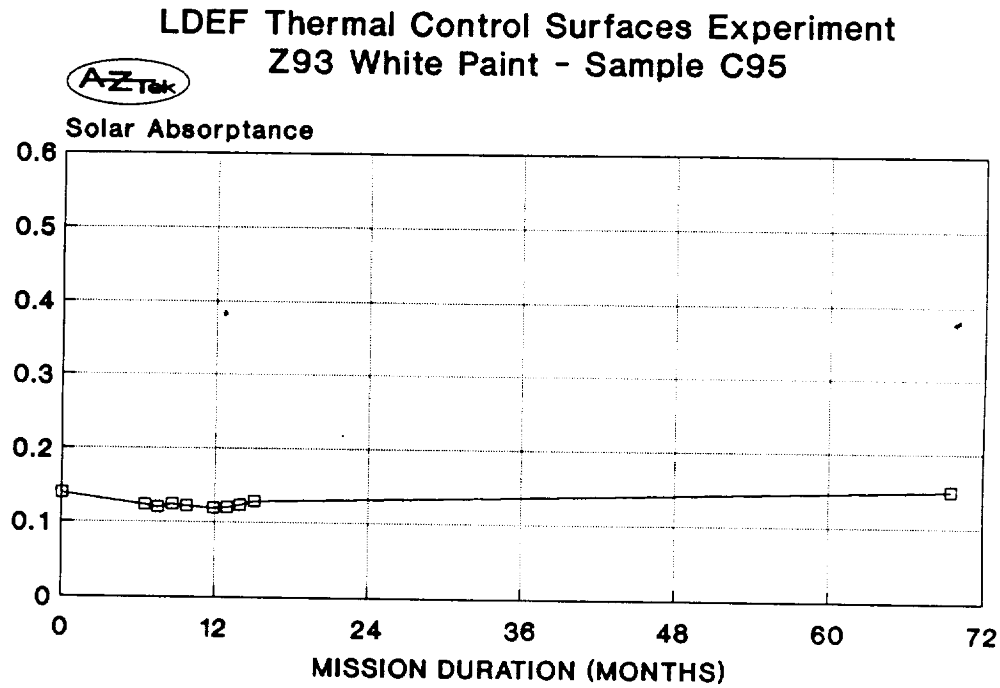



Figure 58 - Flight Performance of Z93

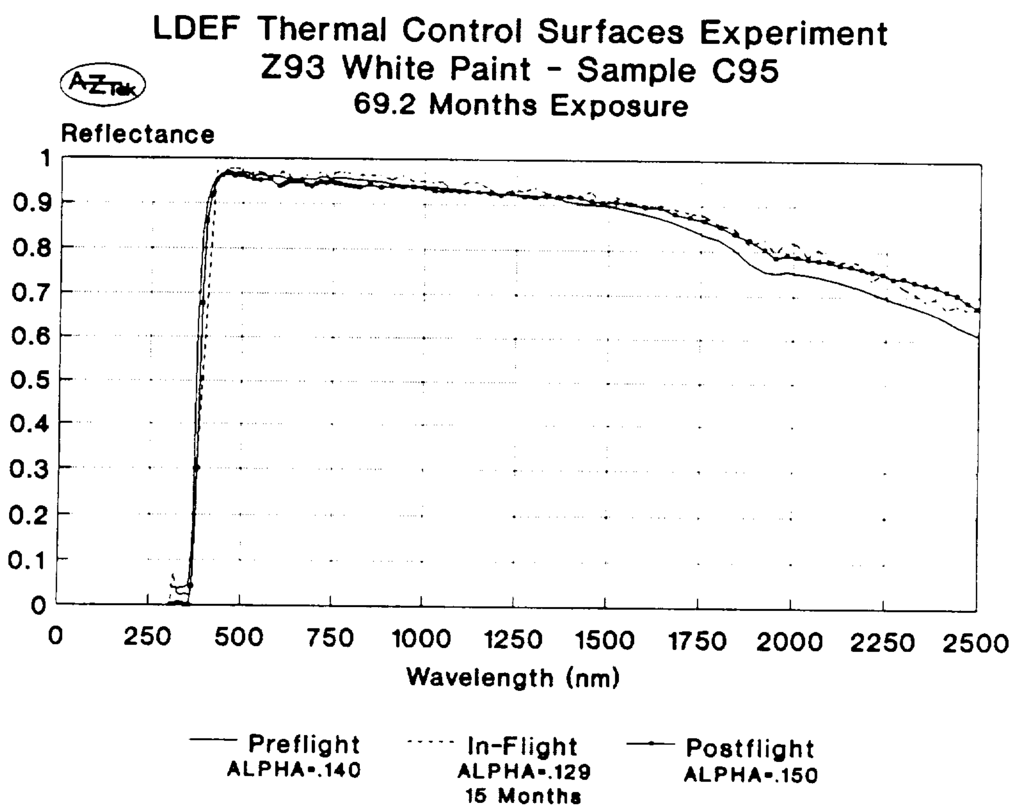



Figure 59 - Reflectance of Z93 Flight Sample

solar absorptance, which is typical of silicate coatings [18] in a thermal vacuum environment. The initial improvement is due to an increased reflectance above 1300 nm. This is offset by a very slow degradation below 1000 nm and results in only a 0.01 overall degradation in solar absorptance for the extended space exposure. Because of the excellent performance of the Z93, it is the leading candidate for the radiator coating for Space Station Freedom.

One concern for Z93 and the other silicate coatings is the effects of micrometeoroid and debris impacts. Figure 60 shows the result of an impact on a Z93 sample. This small impact is about 0.4 mm in diameter and occurred near the edge of the guard ring of the calorimeter. The impact caused a larger area of the coating to break away. The affected area did not propagate throughout the coating and was limited to the immediate area around the impact.

As with the A276 samples, the LDEF space exposure also changed the UV fluorescence in the Z93 samples. The unexposed Z93 coatings fluoresce naturally but much of this fluorescence was quenched by the LDEF exposure. Fluorescence of the ZnO pigment in Z93 and its decrease under UV exposure has been previously reported.[19] This quenched fluorescence in Z93 samples is not confined to the leading edge samples, but is found on LDEF trailing edge samples as well. Figures 61 through 64 are white light and blacklight photographs of samples from the LDEF experiment A0114. A0114 had Z93 samples on both the leading edge (location C9) and on the trailing edge (location C3). The

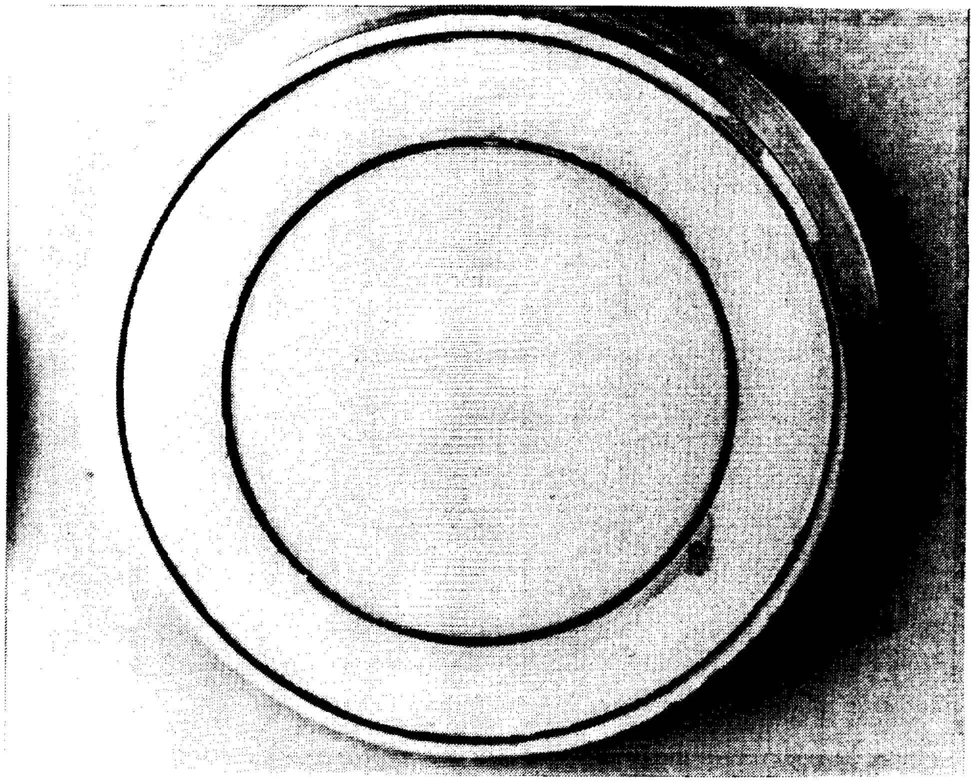


Figure 60 - Post-flight Photograph of Z93

samples were mounted with a cover that had a semicircular exposure window. Under white light, it is difficult to determine what area of the sample was exposed. However, the exposed area becomes very obvious under blacklight. These photographs are used by permission of Dr. J. Gregory (UAH).

### 5.2.3 YB71 White Paint

The YB71 coatings on the TCSE behaved similarly to the Z93 samples. A small increase in the infrared reflectance early in the mission caused a decrease in solar absorptance (see Figures 65 and 66). This was offset by a slow long term degradation resulting in a small overall increase in solar absorptance. The

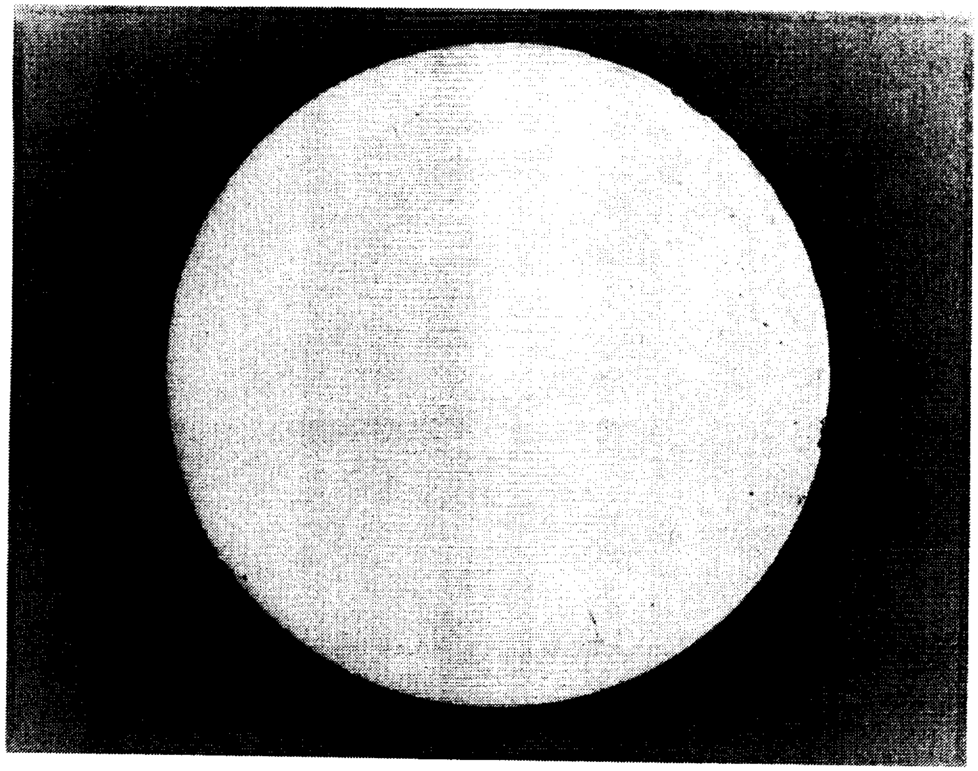


Figure 61 - White Light Post-flight Photograph of Z93 Flight Sample-Leading Edge

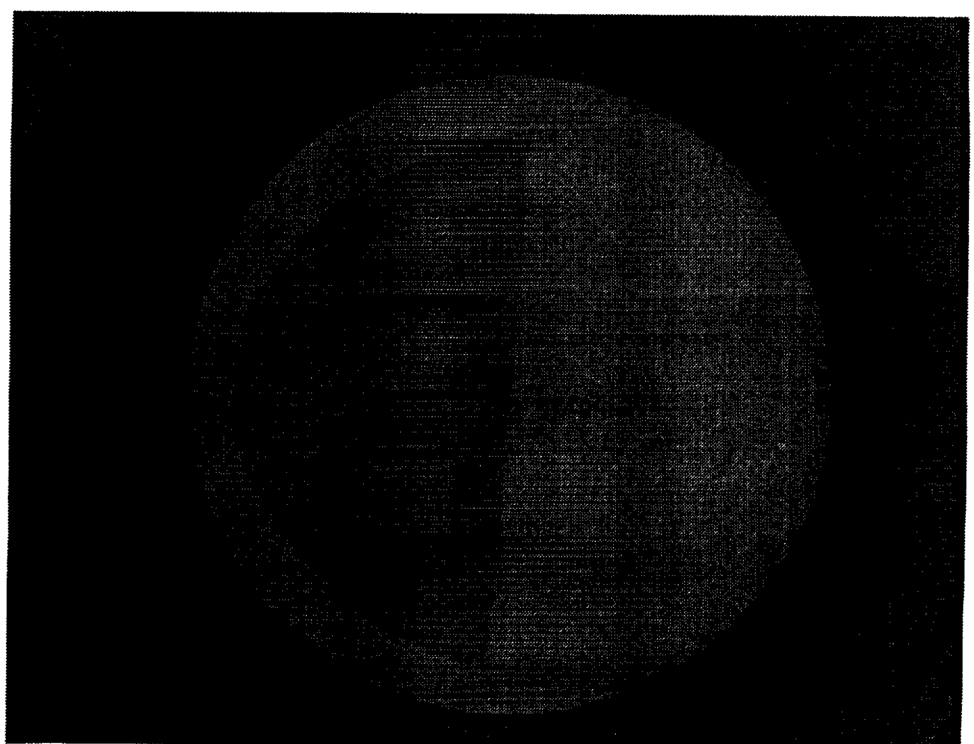


Figure 62 - Black Light Post-flight Photograph of Z93 Flight Sample-Leading Edge

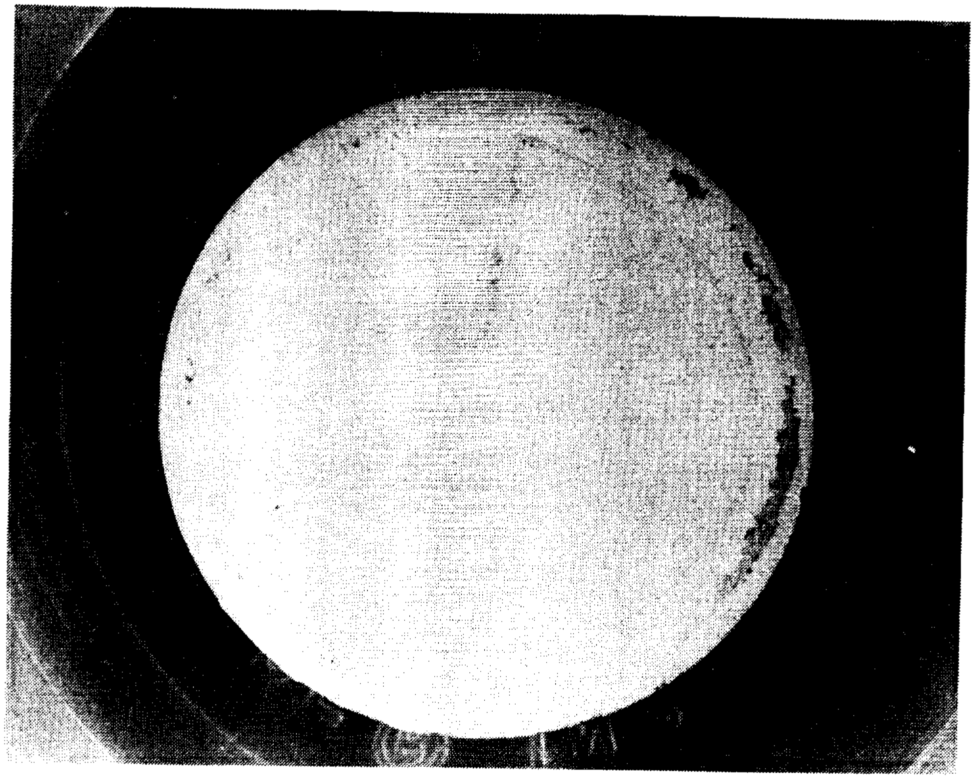


Figure 63 - White Light Post-flight Photograph of Z93 Flight Sample-Trailing Edge

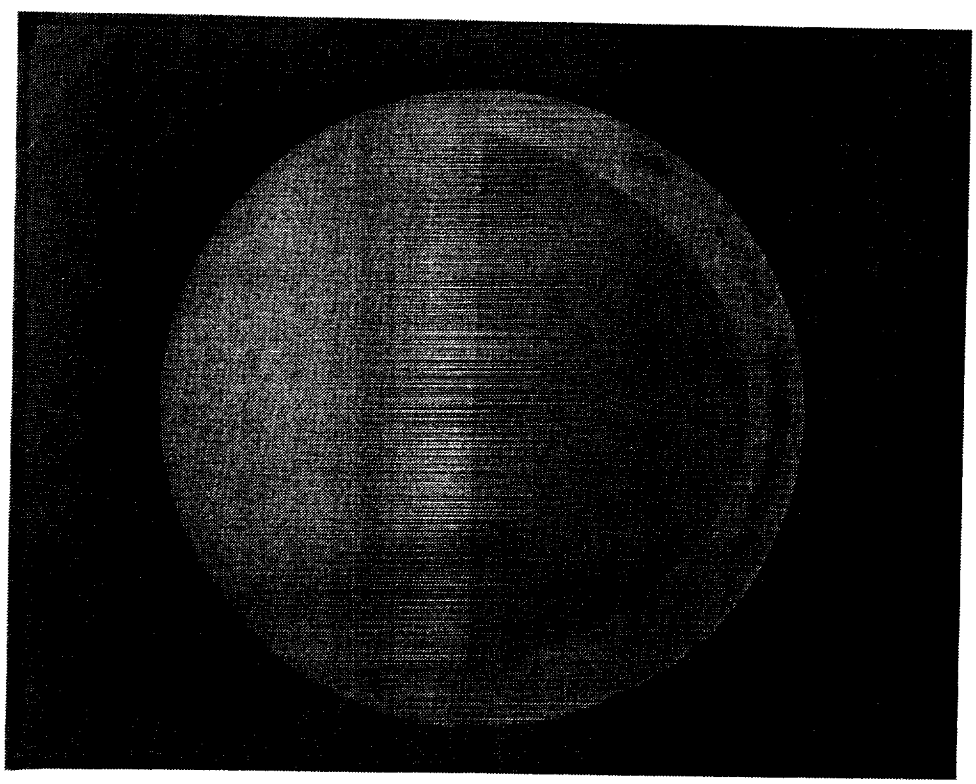


Figure 64 - Black Light Post-flight Photograph of Z93 Flight Sample-Trailing Edge

TCSE YB71 samples were made before the preparation and application parameters for this new coating were finalized. This resulted in a wide spread in the initial solar absorptance for the different samples. The samples with YB71 applied over a primer coat of Z93 had a somewhat lower $\alpha_s$ than the other YB71 samples. Current YB71 samples are consistently below 0.10 solar absorptance.

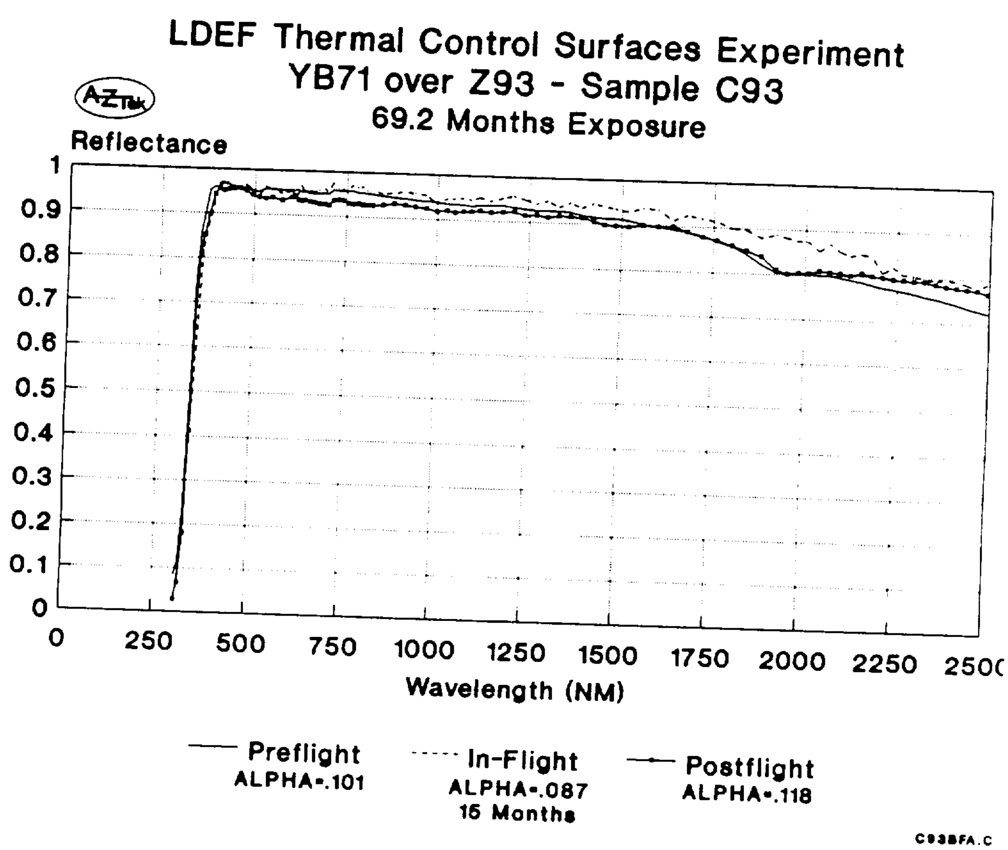



Figure 65 - Reflectance of YB71/Z93 Flight Sample

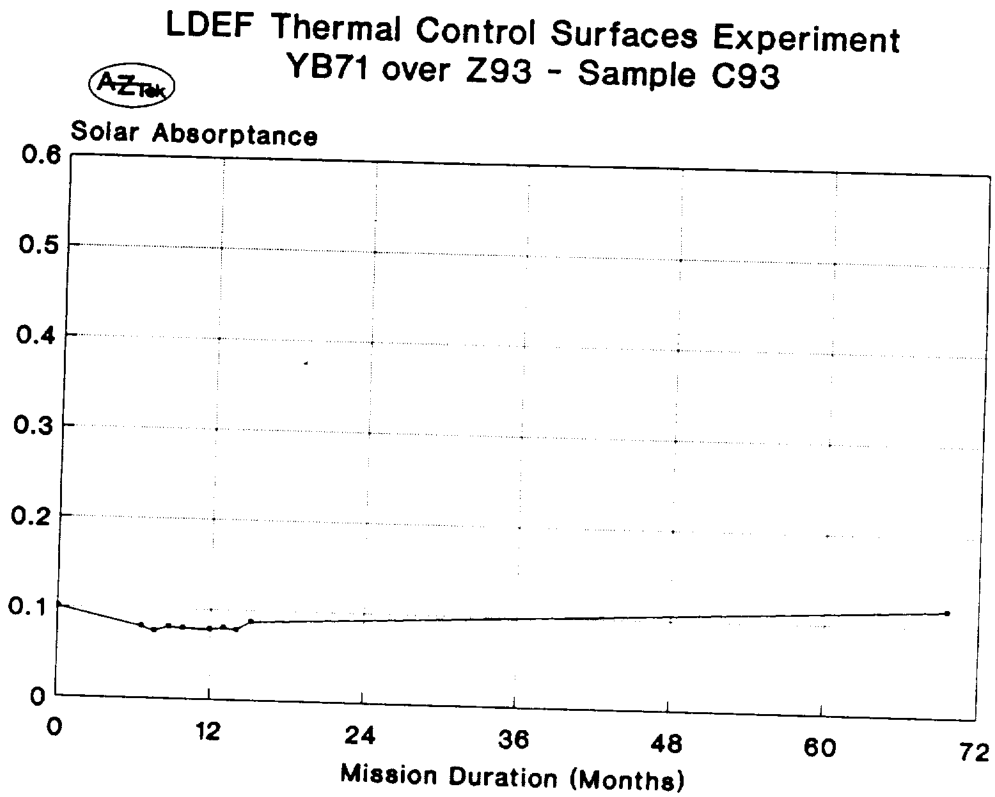



Figure 66-Flight Performance of YB71/Z93

### 5.2.4 S13G/LO White Paint

The S13G/LO samples on the TCSE degraded significantly on the LDEF mission. Figure 67 shows the change in solar absorptance for the LDEF mission of the TCSE S13G/LO calorimeter sample. Figure 68 shows the spectral reflectance measurements of the S13G/LO sample. Figure 69 is a post-flight photograph of an S13G/LO coated calorimeter sample holder. Notice the color grading of the degraded (darker) surface with lighter colors near the edges. As with Z93, the UV fluorescence of the S13G/LO coatings decreased markedly in the flight samples.

Degradation of the S13G/LO samples for the almost 6 year space exposure was expected. However, the magnitude of this

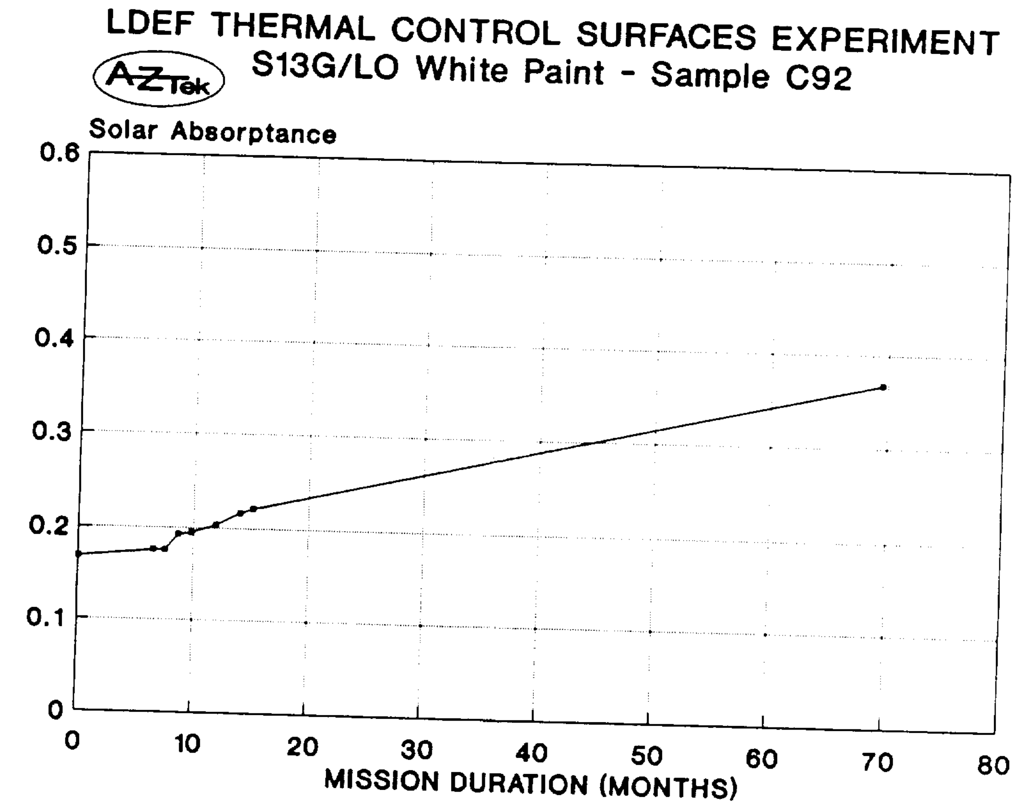



Figure 67 - Flight Performance of S13G/LO

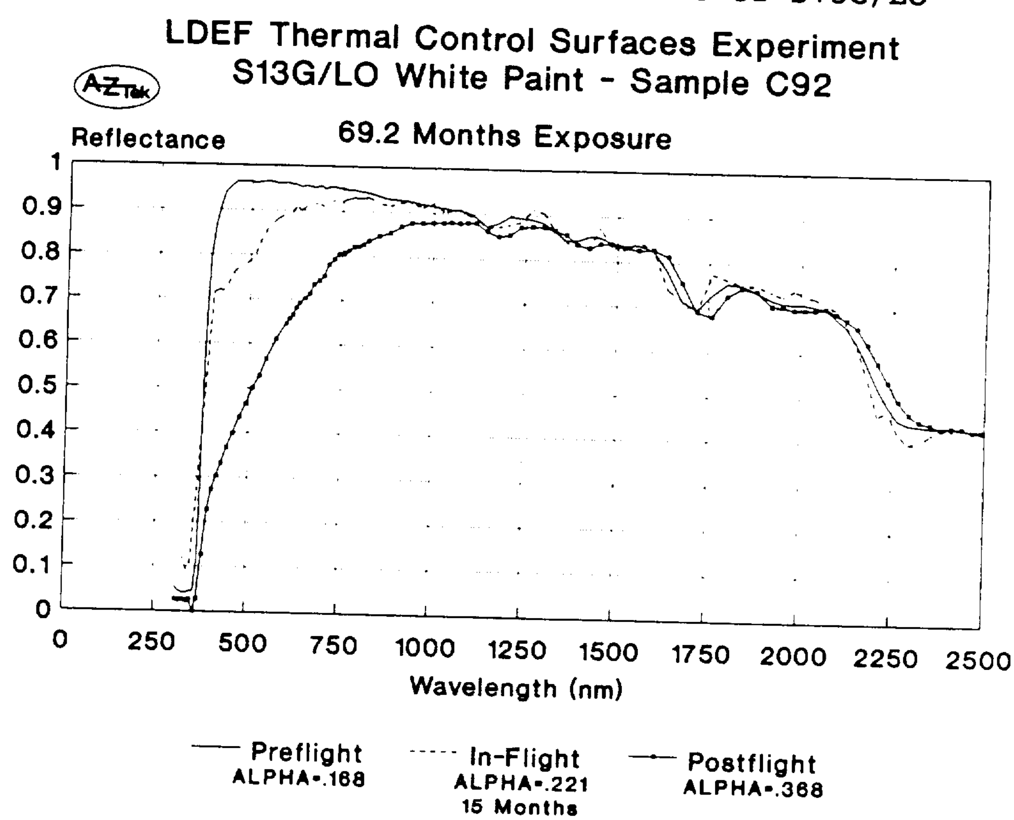



Figure 68 - Reflectance of S13G/LO Flight Sample

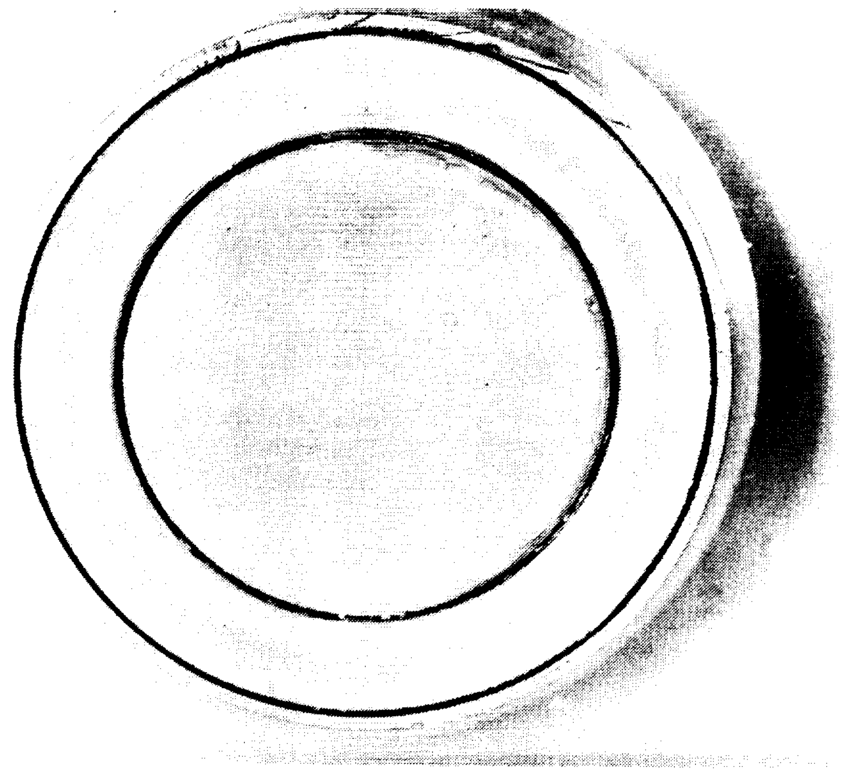


Figure 69 - Post-Flight Photograph of S13G/LO Sample

degradation is significantly greater than ground testing predictions. Figure 70 compares the performance of the S13G/LO and Z93 on the LDEF/TCSE mission to a ground simulated space exposure test previously performed at MSFC.

These data show the flight degradation of S13G/LO to be significantly more than predicted while it is just the opposite for Z93. This is difficult to explain since the two coatings are similar in formulation. Both use ZnO pigment but the S13G/LO has a methyl silicone binder while Z93 has a potassium silicate binder. The S13G/LO pigment particles are encapsulated in potassium silicate. More studies will be required to understand the dichotomy in these results.

The S13G/LO flown on the TCSE is not the currently available formulation. A new silicone binder is used in the current S13G/LO-1 coating.

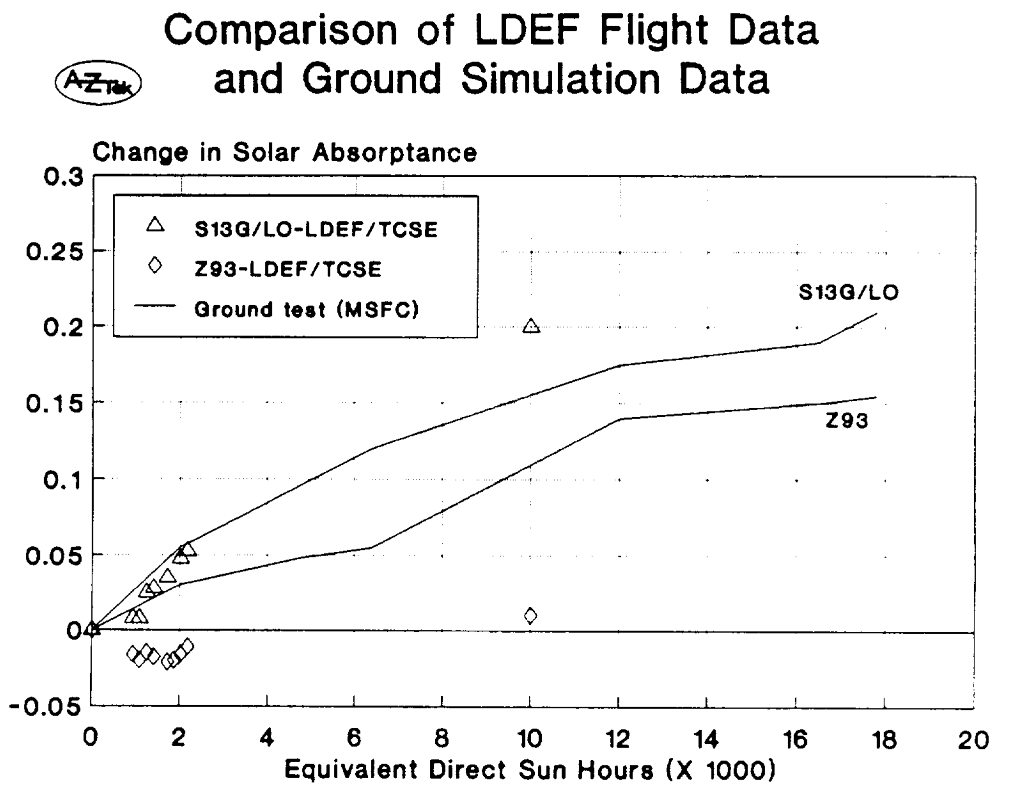



Figure 70-Comparison of Space Flight vs. Ground Simulation Testing

5.2.5 Chromic Acid Anodize

There were two chromic anodize samples on the TCSE sample carousel. These two samples degraded significantly during the first 18 months of the LDEF/TCSE mission as shown by the TCSE in-space measurements (see Figure 71). When the TCSE batteries were depleted (19.5 months mission time), the carousel stopped where one of the two anodize samples was exposed for the remainder of the LDEF mission while the other was protected. Photographs of

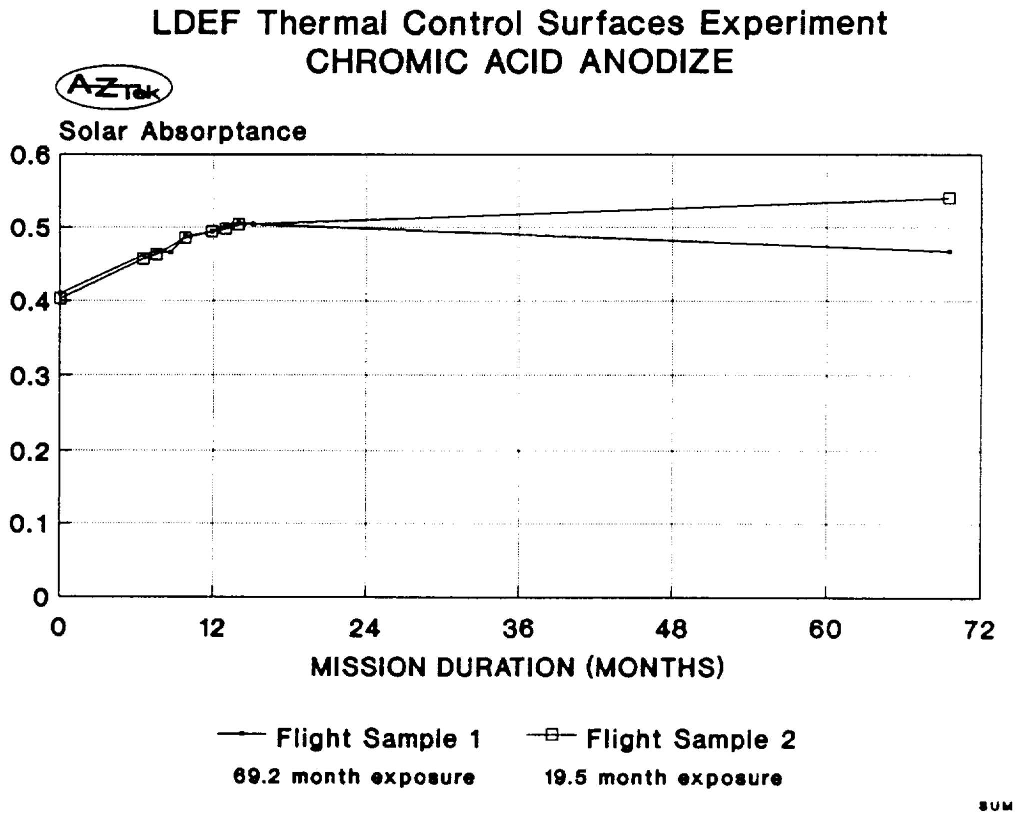



Figure 71 - Flight Performance of Chromic Acid Anodize

the two samples (Figures 72 and 73) show significantly different appearance. The sample with 19.5 months exposure has an evenly colored appearance except for several small surface imperfections. The sample that was exposed for the entire 69.2 month mission has a mottled, washed out appearance. Figures 74 and 75 are the detailed pre- and post-flight reflectance curves for the two anodize samples.

It will require further study to determine why the solar absorptance of the anodize sample that was exposed for the complete mission improved in the latter stages of the mission. The high AO fluence incident on the TCSE samples in the later stages

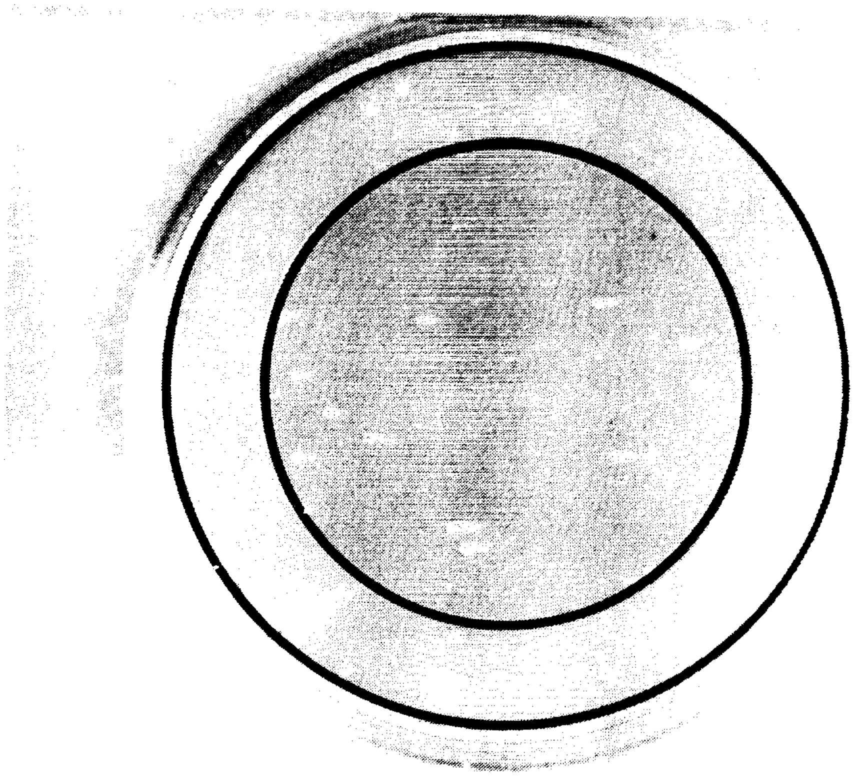


Figure 72 - Anodize Sample with 19.5 Month Exposure

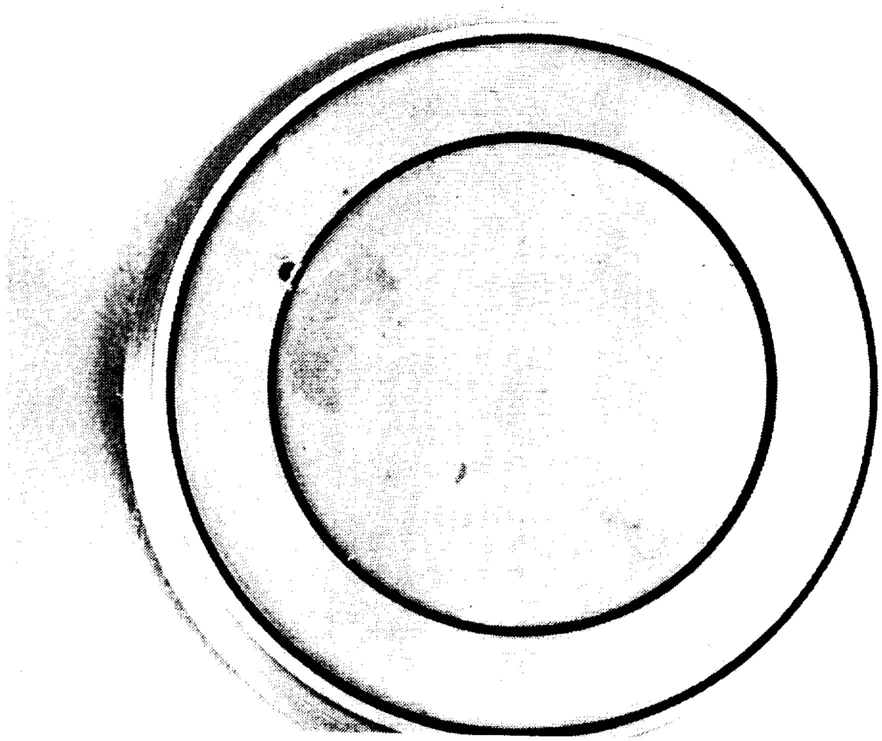


Figure 73 - Anodize Sample with 69.2 Month Exposure

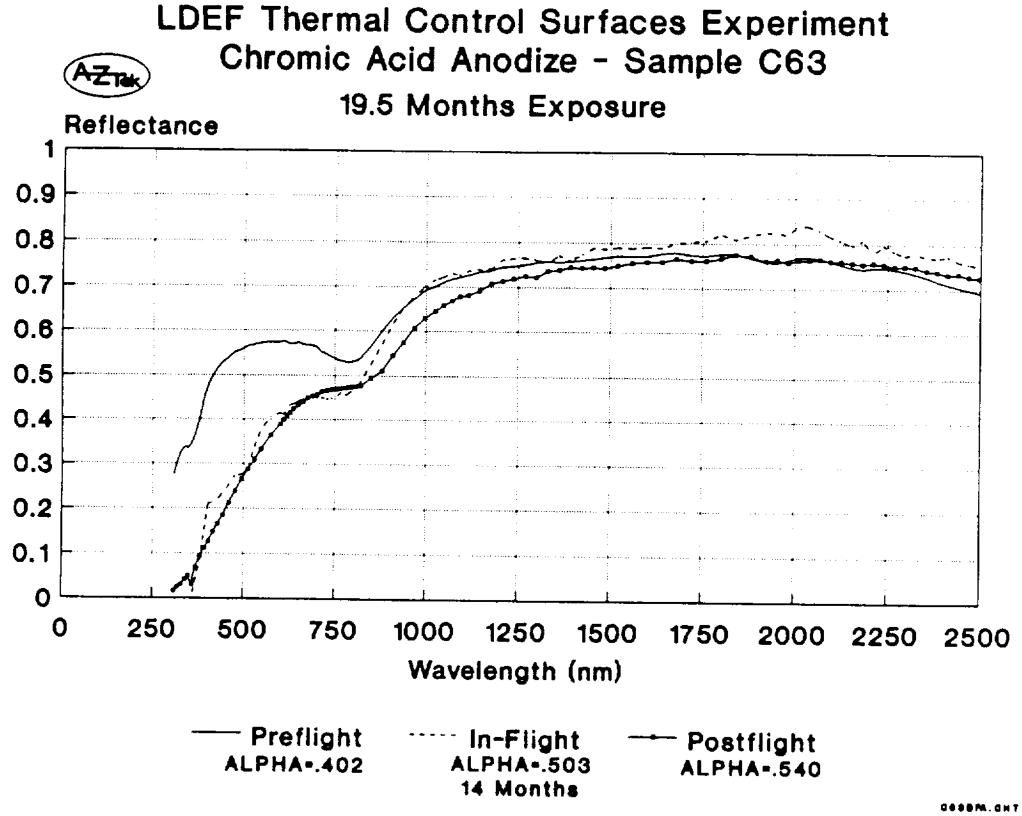



Figure 74 - Reflectance of Anodize Sample (19.5 Months Exposure)

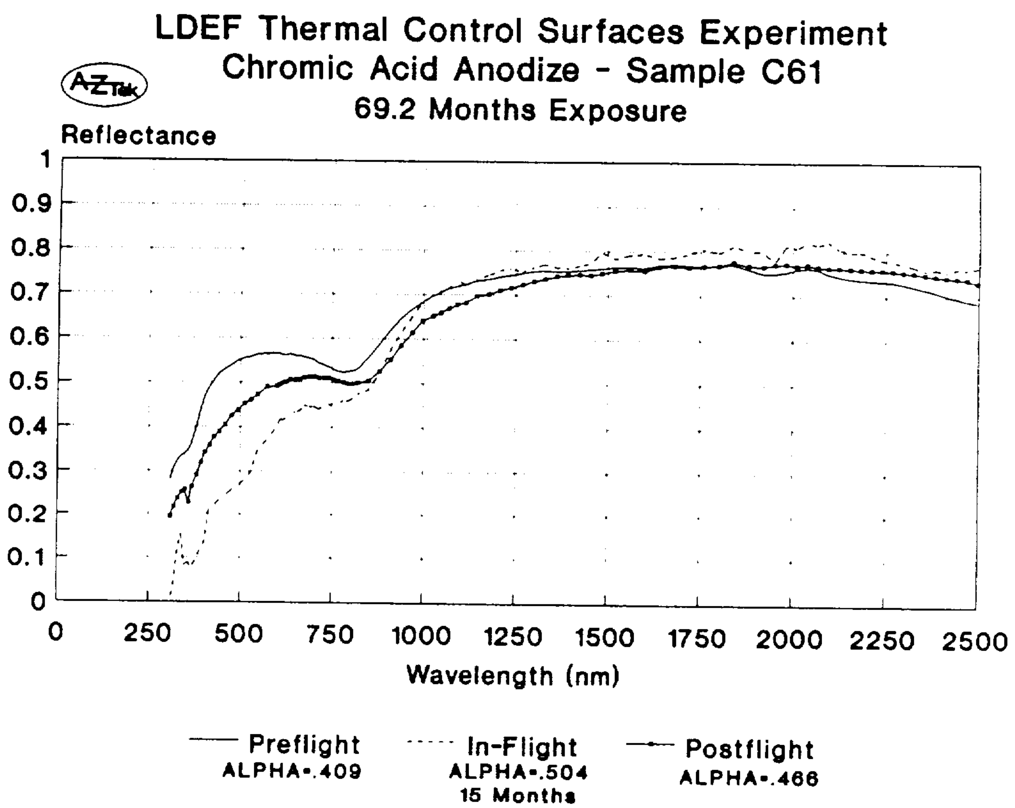



Figure 75 - Reflectance of Anodize Sample (69.2 Months Exposure)

of the mission may have caused this change. It does not appear that the thickness of the oxide layer has been decreased because the emittance of the samples did not change.

### 5.2.6 Silver Teflon Solar Reflector

There were three different silver Teflon materials on the TCSE. The front cover of the TCSE and one calorimeter sample were two mil thick silver FEP Teflon bonded to the substrate with Y966 acrylic adhesive. The other samples were five mil thick silver FEP Teflon (specular and diffuse) and were bonded to the substrate with P223 adhesive.

The silver Teflon surfaces on the TCSE underwent significant appearance changes. The most striking change observed occurred on the silver Teflon exposed in the LDEF RAM direction -- the surface color was changed to a diffuse, whitish appearance. This change, as depicted in Figure 76, is caused by the eroding effect of atomic oxygen and results in a rough, light scattering surface. Preliminary measurements indicate a loss of about one mil of Teflon for the TCSE mission in addition to the roughened surface. A one mil loss of Teflon from the two mil samples would cause a significant loss of emittance, as was measured.

While the AO roughened silver Teflon surfaces underwent striking appearance changes, the reflectance and solar absorptance did not degrade significantly due to this effect. For the 5 mil coatings with P223 adhesive, only small changes in reflectance (see Figure 77) and solar absorptance were measured. In

addition there was very little change in emittance (see Figures 47-50 in Section 5.2).

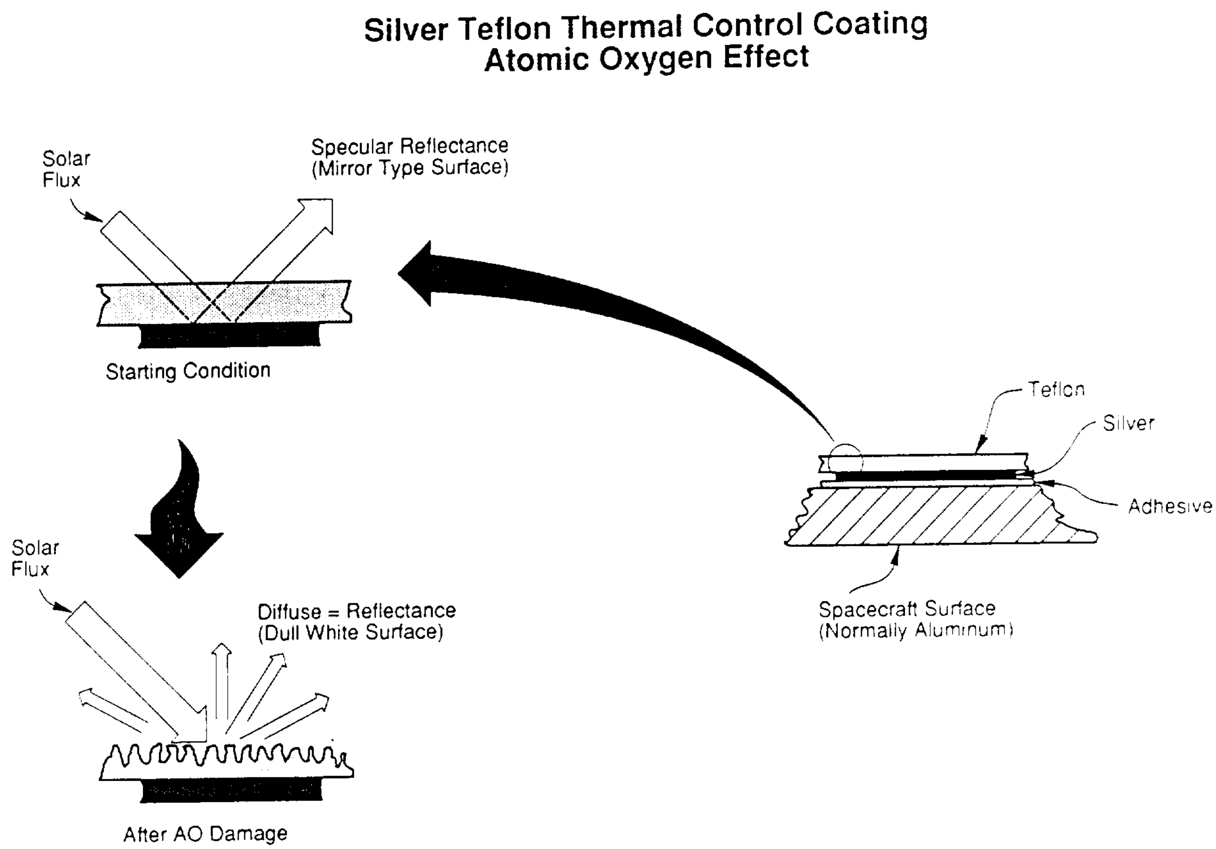



Figure 76 - Silver Teflon Thermal Control Coating Atomic Oxygen Effect

The two mil silver Teflon coatings, however, did degrade significantly. The coatings had a brown discoloration. Laboratory evaluation of these coatings with Nomarski microscopes revealed the discoloration was under the Teflon surface. Further investigation determined that the brown discoloration is associated with cracks in the silver - inconel metalized layer. Laboratory tests show that the application of the pre-adhesive type silver Teflon can crack the metalized layers. Removal of the paper backing on the adhesive and removal of air bubbles from

beneath the silver Teflon can over-stress the metal layers causing significant cracking. It appears that a component of the adhesive migrated through the cracks into the interface with the Teflon over the long exposure to thermal vacuum. Subsequently, this internal contaminant was degraded by solar UV exposure causing the brown appearance. As a result, the reflectance decreased (see Figure 78) and more than doubled the solar absorptance.

Figure 79 is a photograph of a section of the TCSE front cover showing a demarcation line where part of the surface was exposed and part was protected by a small secondary cover. The protected area has the characteristic mirror-like finish while the exposed area (foreground) is whitish with brown streaking. The brown streaking is apparent only where it was exposed to the space environment.

The rate of change in reflectance in the silver Teflon active samples, and its resulting solar absorptance, did not change rapidly early in the TCSE mission. Figure 80 shows only a small increase in solar absorptance through the first 16 months of exposure. This indicates that this internal contamination and subsequent optical degradation occurs slowly over long space exposure.

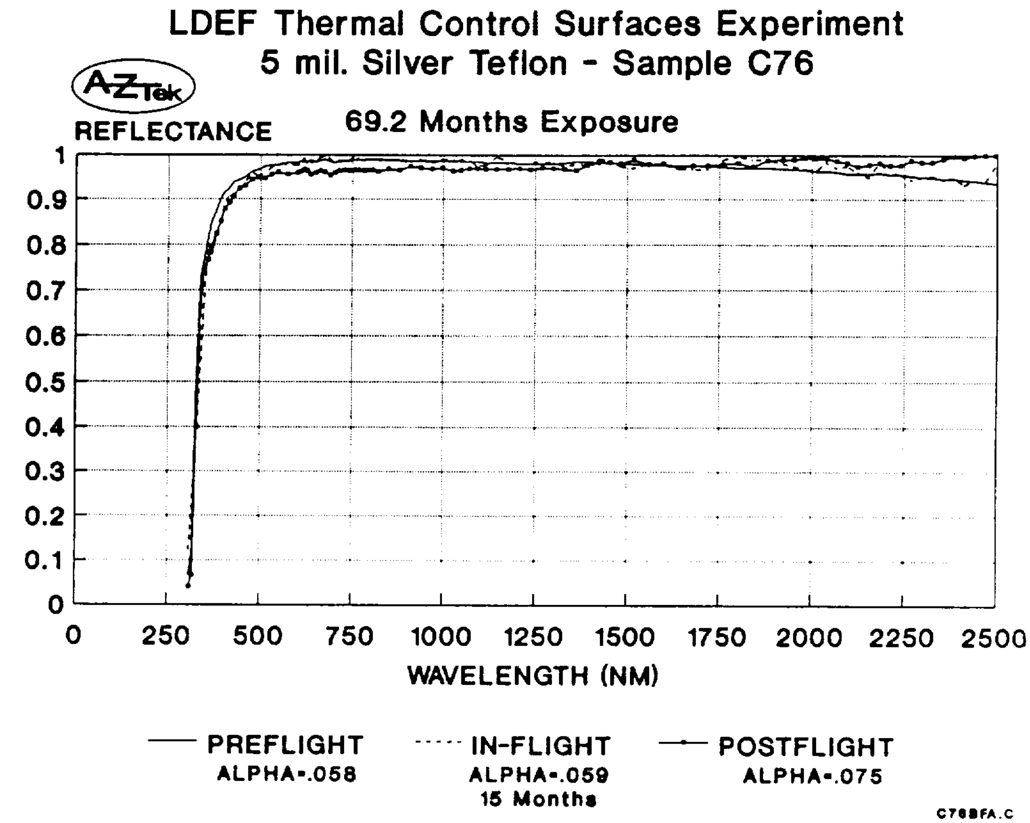



Figure 77 - 5-mil Silver Teflon Reflectance Curve

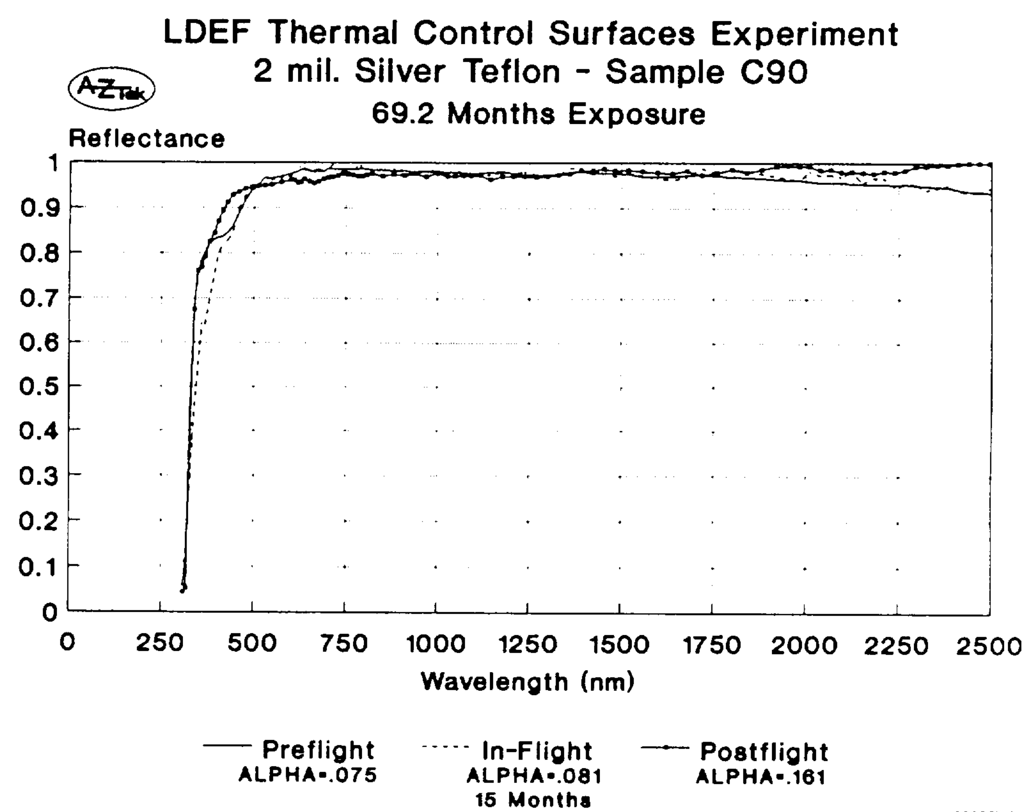



Figure 78 - 2-mil Silver Teflon Reflectance Curve

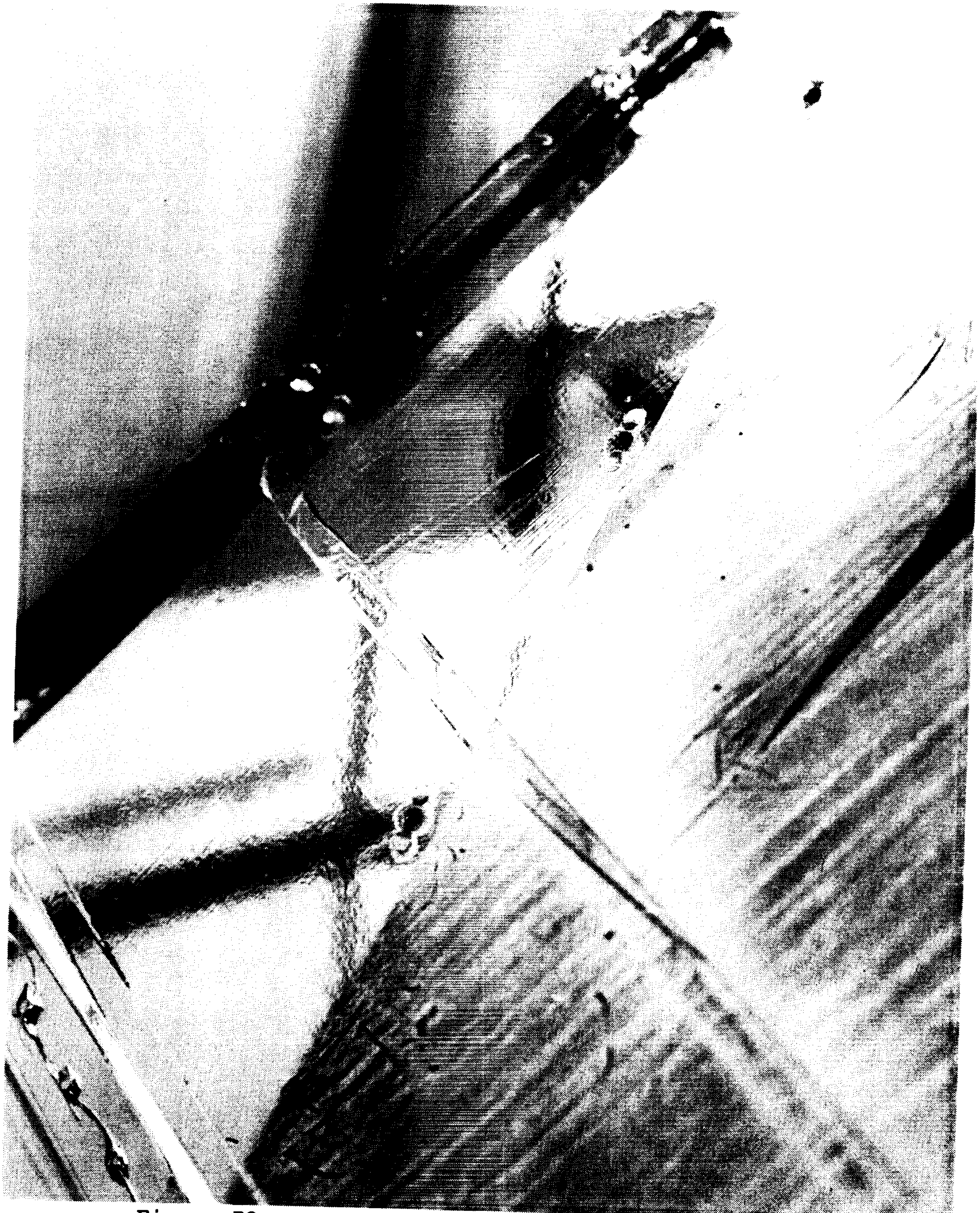


Figure 79 - A Section of the TCSE Front Cover

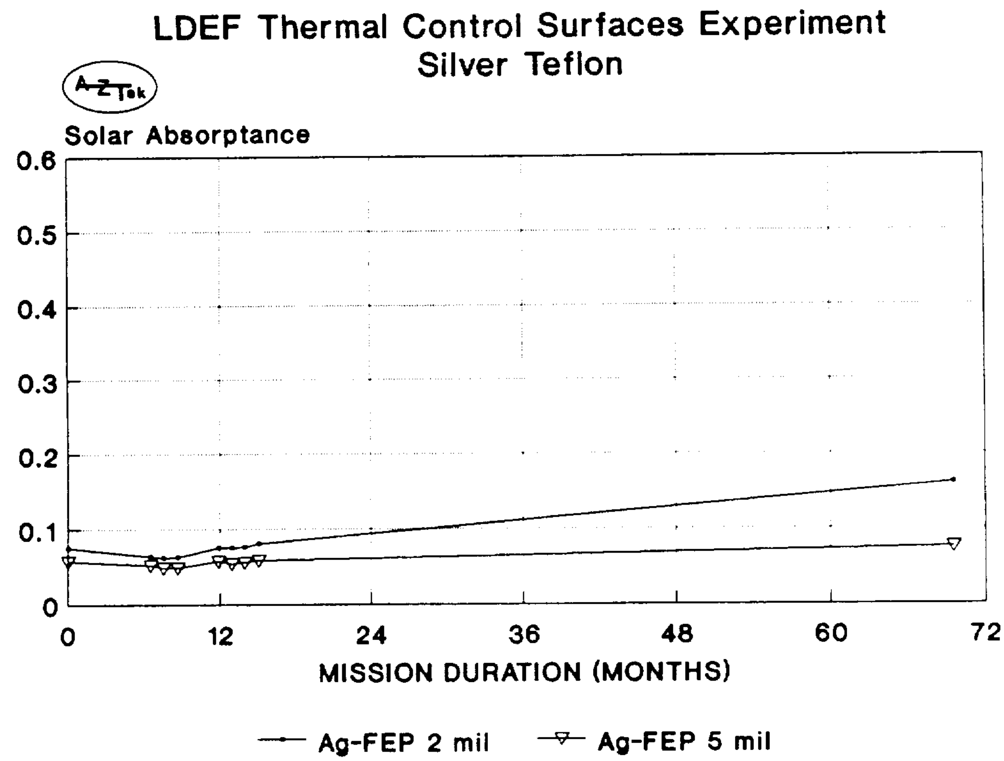



Figure 80 - Flight Performance of Silver Teflon

### 5.2.7 White Tedlar Film

White Tedlar is another material that was expected to degrade over the 5.8 year LDEF mission due to solar UV exposure. Instead, the reflectance properties of this material improved slightly, as shown in Figures 81 and 82. The surface remained diffuse and white, similar to pre-flight observations. As with A276, Tedlar has been shown to be susceptible to AO erosion.[7] The erosion effect of AO is the apparent reason for the lack of surface degradation of these flight samples.

The TCSE in-flight data shows that only a small degradation in solar absorptance was seen early in the LDEF mission. This indicates that, as with the A276 samples, there was sufficient AO

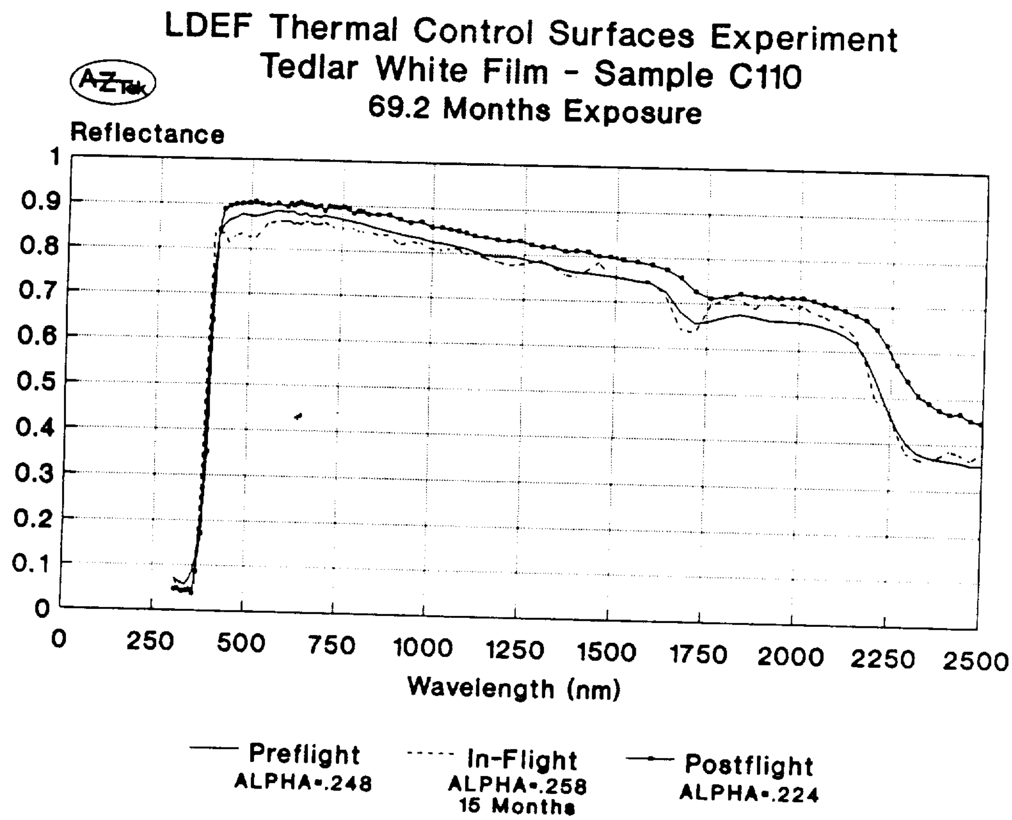



Figure 81 - White Tedlar Reflectance Curve

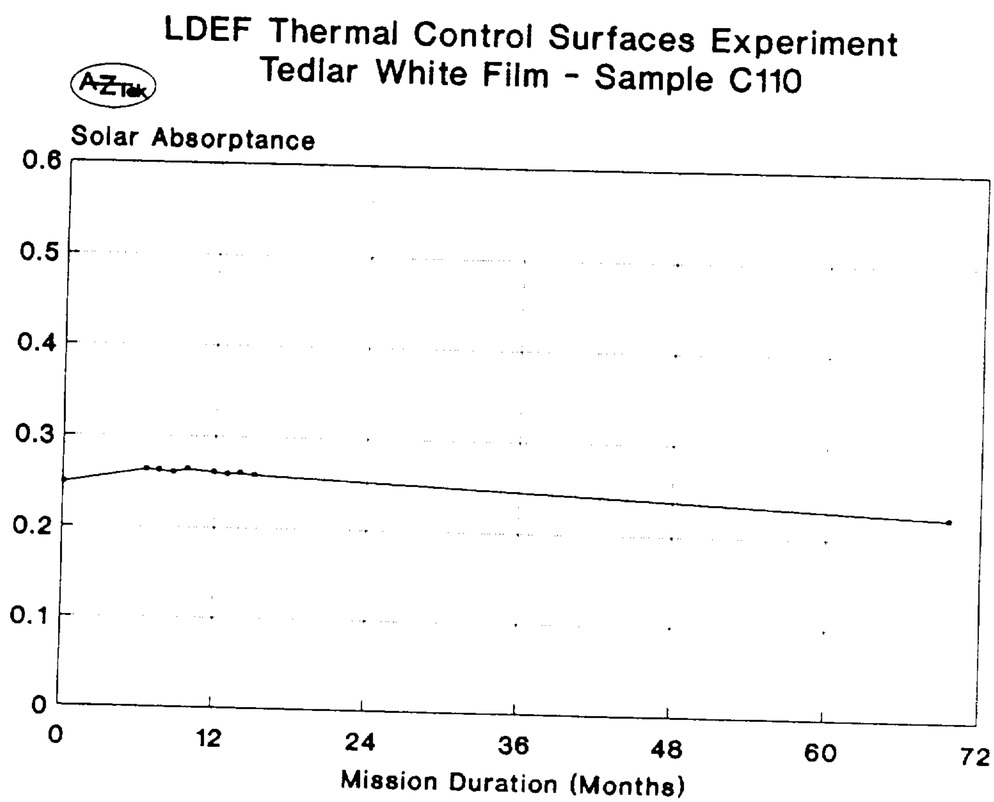



Figure 82 - Flight Performance of White Tedlar

early in the mission to erode away damaged material or otherwise inhibit significant degradation. The subsequent high AO fluence then eroded away all the damaged surface materials and even provided a slight improvement in solar absorptance. Similarly with the other samples, additional analyses are planned to better define these effects. The Tedlar control samples show a small UV fluorescence, which was not apparent in preliminary measurements of the flight samples.

### 5.2.8 Black Paints

Two different black paints were flown on the TCSE - IITRI D111 and Chemglaze Z302. D111 is a diffuse black paint that performed very well with little change in either optical properties or appearance as a result of the TCSE mission. Figure 83 shows the reflectance of the D111 Black Paint and Figure 84 is a post-flight photograph of the sample. The D111 samples had some small imperfections in the coating that were seen in the pre-flight inspections.

Z302 gloss black was the other black coating flown on the TCSE. Z302 has been shown to be susceptible to AO exposure.[1] In anticipation of these erosion effects, protective OI650 and RTV670 coatings were applied over some of the Z302 samples to evaluate their effectiveness. As expected, unprotected Z302 was heavily eroded by the AO exposure. Two of the TCSE Z302 coatings were exposed to the environment for the total 5.8 year LDEF mission. These unprotected Z302 sample surfaces eroded down to the primer coat. Two other samples were exposed

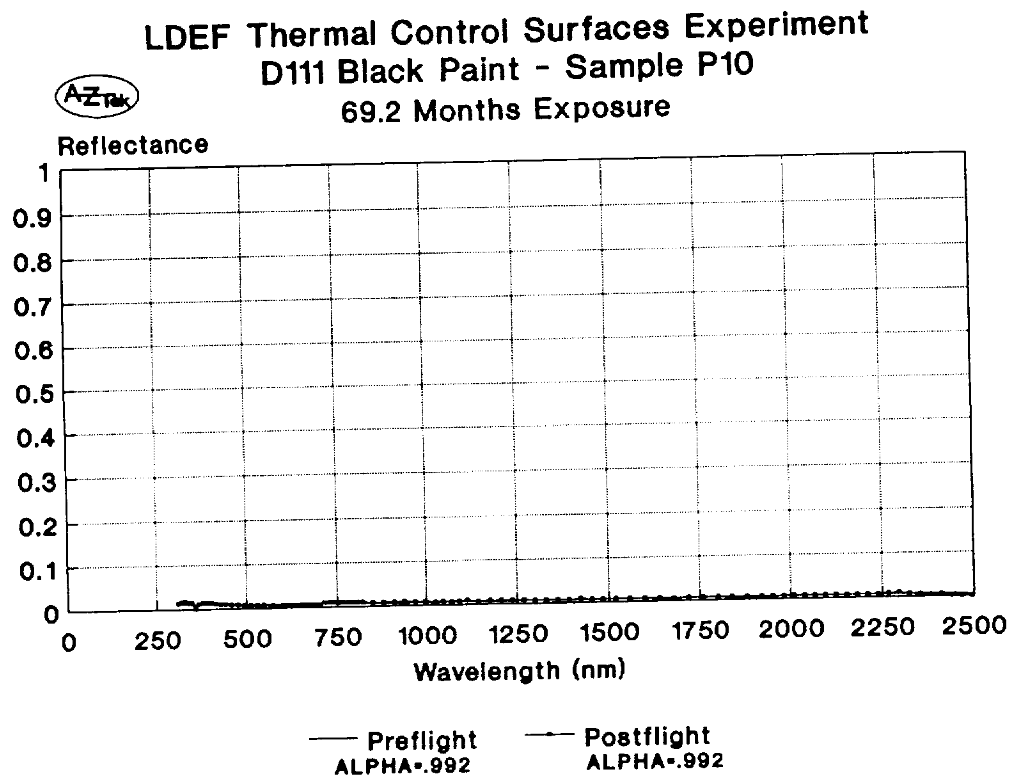



Figure 83 - Reflectance of D111 Flight Sample

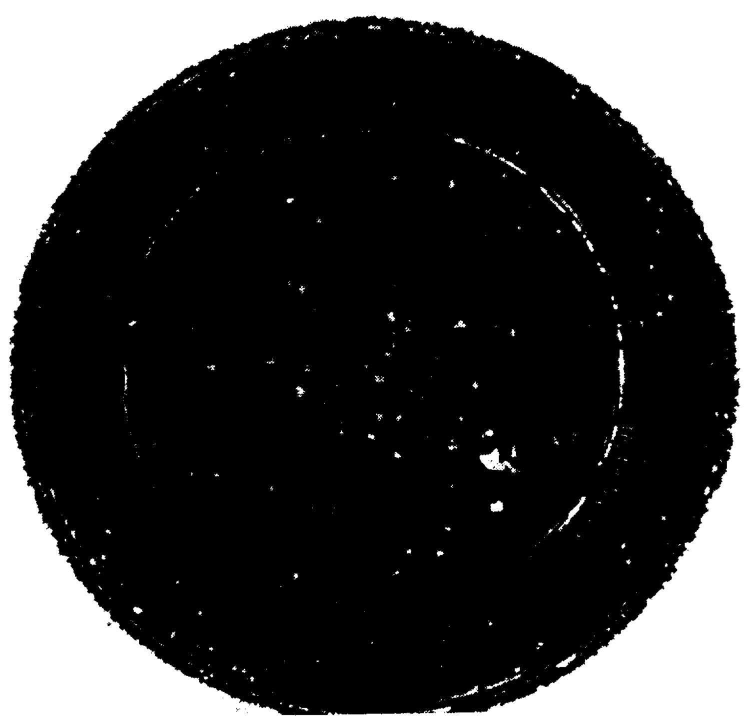


Figure 84 - Post-flight Photograph of D111 Black Paint

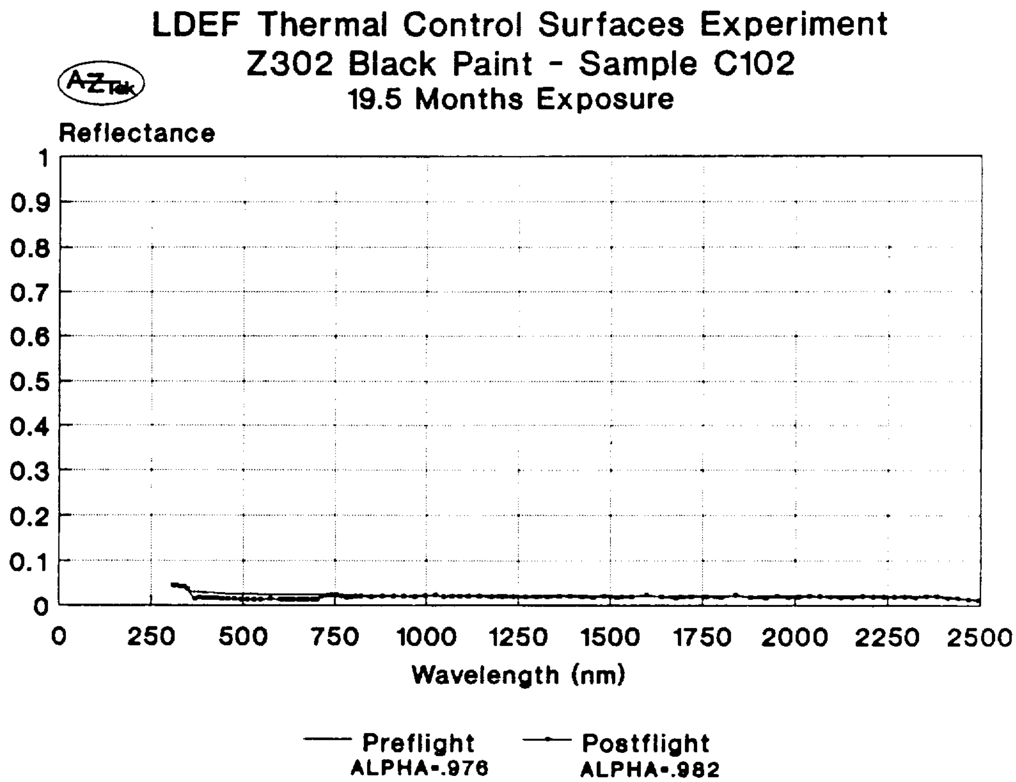



Figure 85 - Reflectance of Z302 Black Paint

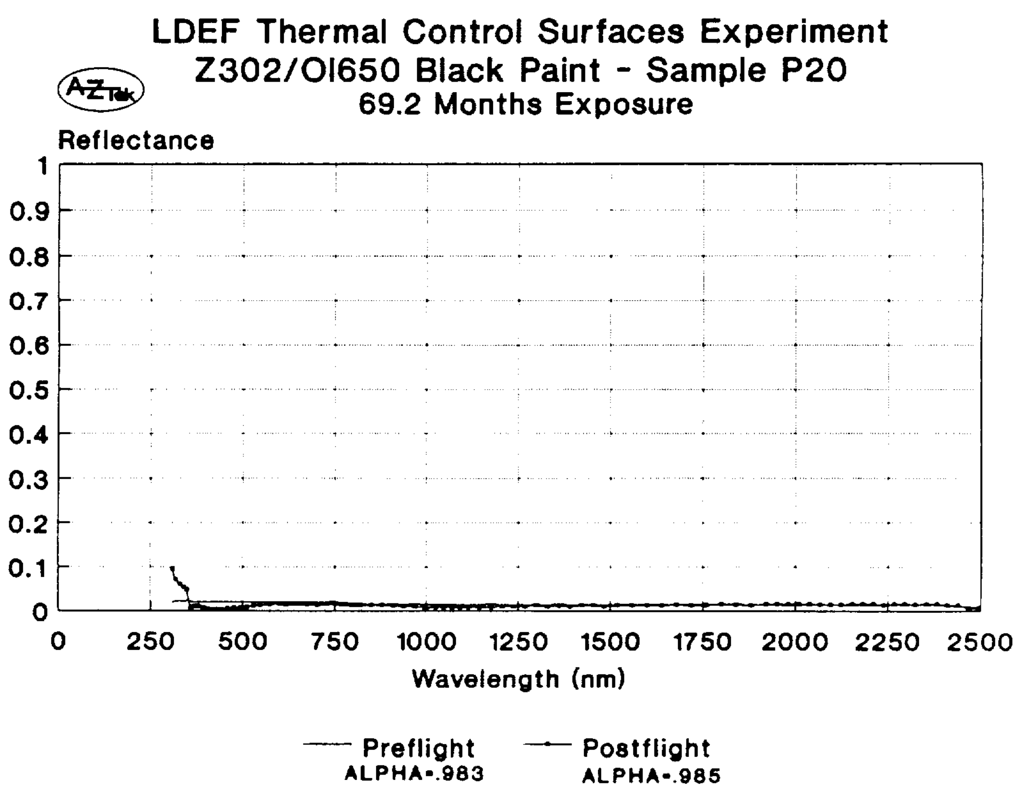



Figure 86 - Reflectance of OI650 over Z302 Black Paint

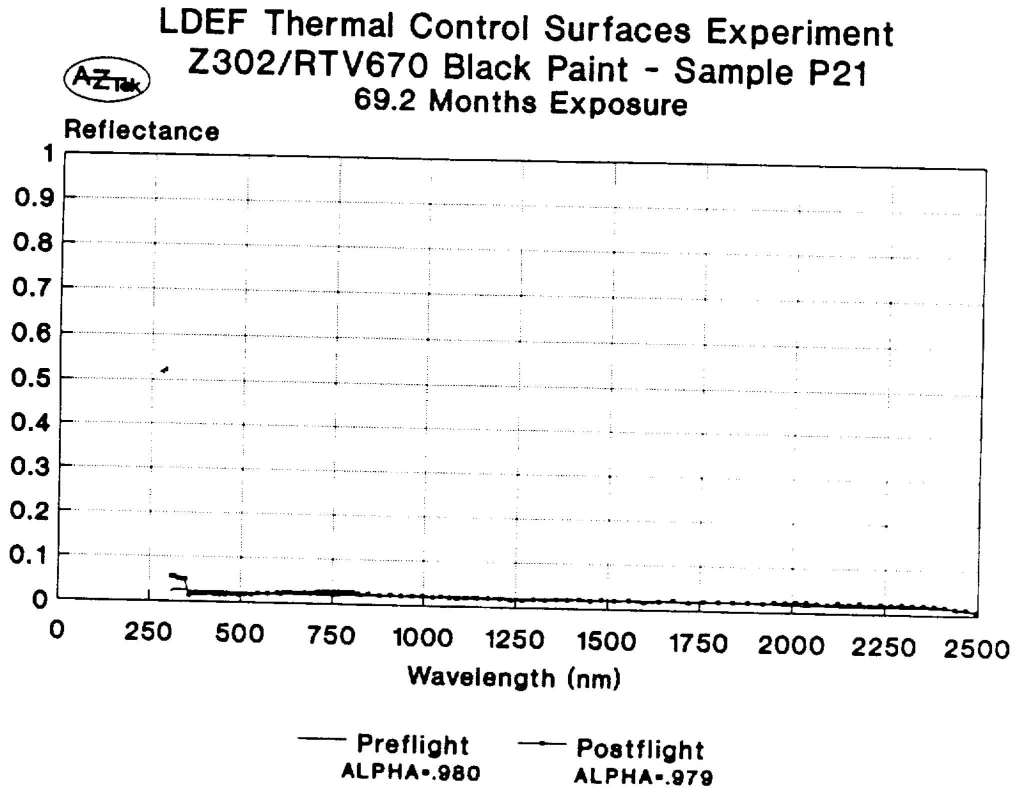



Figure 87 - Reflectance of RTV670 over Z302 Black Paint

for only 19.5 months and, while they did erode, still had good reflectance properties (see Figures 86 and 87).

The overcoatings for the Z302 behaved similarly to the overcoatings on the A276 samples. The Z302 appears to have been protected by the overcoatings but the overcoats cracked and crazed (see Figures 88 and 89). The coatings that were applied to the calorimeter sample holders are believed to have peeled away from the substrate because of the wider temperature excursions of these thermally isolated samples.

In addition, the fluorescence of the Z302 samples changed due to the LDEF exposure. Using a short wavelength UV black light, the unprotected Z302 exhibited a pale green fluorescence while the overcoated samples fluoresced bright yellow. Initial

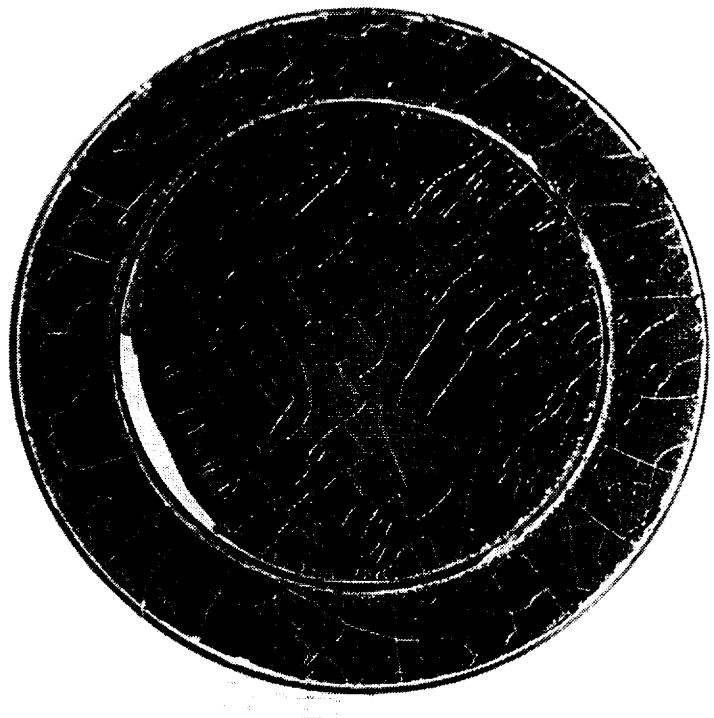


Figure 88 - Post-flight Photograph of OI650 Overcoated Z302

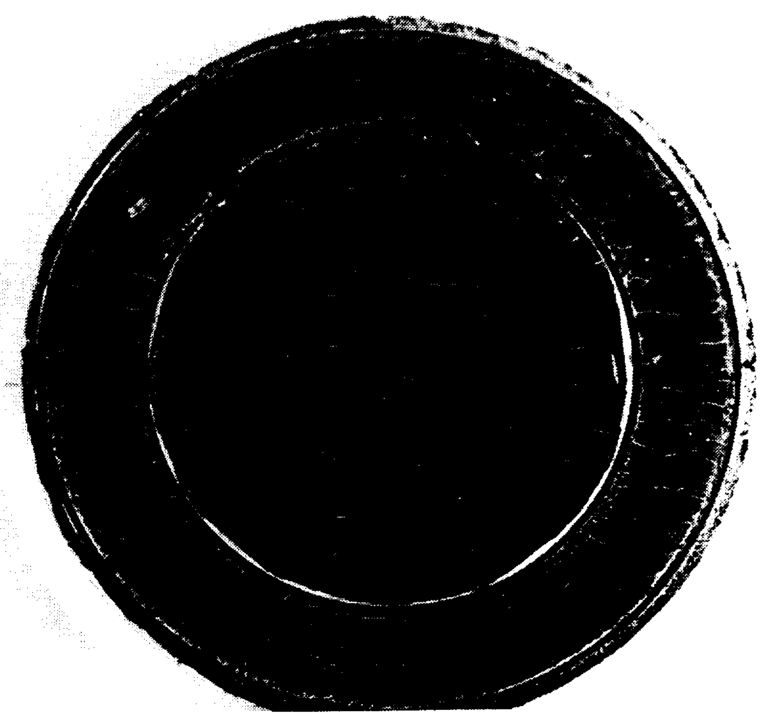


Figure 89 - Post-flight Photograph of RTV670 Overcoated Z302

spectral analysis of the Z302 samples show that the control samples naturally fluoresce; however, the LDEF exposure caused a wavelength shift and an increase in the magnitude of the fluorescence. Additional studies will be performed to fully characterize these effects.

## 6.0 SUMMARY

The TCSE has provided excellent data on the behavior of materials and systems in the space environment. Expected effects did happen, but in some cases the magnitude of these effects were more or less than expected or were offset by competing processes. A number of unexpected changes were also observed, such as the changes in the UV fluorescence of many materials. In all, the TCSE was an unqualified success. However the TCSE did incur several system anomalies that have made some of the post-flight analyses more difficult. For instance, the loss of the first six months of flight data due to the recorder malfunction is probably the most significant.

The performance of the materials tested on the TCSE ranges from very small changes to very large changes in optical and mechanical properties. The stability of some of the materials such as Z93, YB71 and silver Teflon (with P223 adhesive) shows there are some thermal control surfaces that are candidates for long term space missions. The materials that significantly degraded offer the opportunity to study space environment/material interactions.

The TCSE is the most comprehensive thermal control surfaces experiment ever flown. The TCSE is also the most complex system, other than the LDEF with experiments, recovered from space after extended exposure. The serendipitous extended exposure of the prolonged LDEF mission only added to the significance of the data gathered by the TCSE. This analysis effort has only begun the process of deriving the greatest benefit from the TCSE. It will

require many years of concentrated effort before a new experiment can be designed, built, and flown to collect similar long term space exposure data. It is imperative that the analyses of the TCSE be completed in a timely manner so the results can benefit the next generation of space vehicles, instruments, and structures.

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**16. Abstract**


The behavior of materials in the space environment continues to be a limiting technology for spacecraft and experiments. The Thermal Control Surfaces Experiment (TCSE) aboard the LDEF is the most comprehensive experiment flown to study the effects of the space environment on thermal control surfaces. Selected thermal control surfaces were exposed to the LDEF orbital environment and the effects of this exposure measured. The TCSE combined in-space orbital measurements with pre- and post-flight analyses of flight materials to determine the effects of long term space exposure. The TCSE experiment objective, method and measurements are described along with the results of the initial materials analysis. The TCSE flight system and its excellent performance on the LDEF mission is described. A few operational anomalies were encountered and are discussed.


**17. Key Words (Suggested by Author(s))**

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